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THERMOREGULATORY CONSEQUENCES OF RESONANT MICROWAVE EXPOSURE

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This report has been reviewed and is approved for publication.

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Four experiments were conducted in which it was shown that behavioral and autonomic thermoregulatory responses are mobilized in an orderly fashion when squirrel monkeys undergo whole-body exposure at the resonant frequency, 450 MHz. The threshold for alteration of thermoregulatory behavior is about 3 mW/cm^2, equivalent to an SAR of nearly 2 W/kg. Behavioral responses serve to regulate the skin temperature at the normally preferred level. Because of the deep penetration of the radiation at resonance, this regulation results in a stable hyperthermic offset or bias in the deep body temperature. This situation is identical to that which occurs during exercise. Although not yet studied, we presume that the magnitude of this offset will be a direct function of the energy deposited in the body or SAR. Autonomic responses of peripheral vasodilation and sweating, manifested on the skin surface, are stimulated at SARs similar to the behavioral threshold, indicating the possibility that such responses could serve as auxiliary sensory cues to behavior.

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SUMMARY

Ample evidence is available to support the conclusion that exposure to low-intensity radiofrequency (RF) fields influences the normal responses, both autonomic and behavioral, that regulate the body temperature. Even when no changes can be measured in the deep or peripheral temperatures of the body, sensitive thermoregulatory responses are mobilized to dissipate the heat generated in body tissues by the absorption of thermalizing energy from RF sources in the environment. These mechanisms are so efficient that, even when field strengths are significant, only modest increments in body temperatures may occur.

In the past, we have used the squirrel monkey as an animal model to determine the minimal incident energy (in mW/cm^2) derived from 2450-MHz continuous wave (CW) microwaves that is necessary to lower an elevated metabolic heat production in the cold, alter peripheral vasomotor tone in thermoneutral environments, initiate thermoregulatory sweating in the heat, and alter thermoregulatory behavior. In all cases, the threshold power density was remarkably similar (4-8 mW/cm^2), a finding we interpreted as indicating a common thermal basis for the response change. The whole-body specific absorption rate (SAR) at threshold was equivalent to 15-20% of the resting metabolic heat production (M̲) of the animal subjects. Above the threshold level, we found that the field strength tolerated (i.e., that which produces a rise in body temperature of less than 2° C) depends upon both the type of response that can be mobilized (behavioral or autonomic) and, in the latter case, the prevailing environmental temperature during the RF exposure. At 2450 MHz, power densities up to 70 mW/cm^2 (SAR = 10.5 W/kg) are well tolerated when the animal controls the temperature of its environment behaviorally. In constant-temperature environments, with behavioral thermoregulation absent, reliance upon autonomic heat loss responses yields lower tolerance levels that vary in curvilinear fashion with ambient temperature (Ta). Steady-state thermal balance was maintained by squirrel

monkeys at a power density up to 60 mW/cm^2 (SAR = 9 W/kg) at Ta=20 °C, 45 mW/cm^2 (SAR = 6.75 W/kg) at Ta=26 °C, and 20 mW/cm^2 (SAR = 3 W/kg) at Ta = 32 °C. These tolerance levels are readily understood in terms of the thermoregulatory capabilities of the subject animal, the limiting factor in all cases being the capacity to lose body heat through sweating.

Exposure of organisms to the resonant frequency is believed to be a special case of RF exposure because, under these conditions, the energy is maximally absorbed by tissues located deep in the body. Under such conditions, it is possible that thermoregulatory responses, including thermoregulatory behavior, are inadequate to cope with substantial thermalization of deep tissues and thus to prevent severe hyperthermia. The experiments reported here were designed to explore this possibility, using the squirrel monkey model we have found so useful in the past. A frequency of 450 MHz was selected as providing optimal energy absorption for ungrounded animals of this species.

A new exposure facility, incorporating a source of 450 MHz CW microwaves, was built and instrumented appropriately to both control and measure changes in thermoregulatory behavior and correlated autonomic thermoregulatory responses. Four experiments were conducted in this facility; these were designed to determine (1) the threshold absorbed energy, during brief far field exposure of the whole body, that would reliably alter thermoregulatory behavior, (2) the efficiency of this behavior in the steady state, and (3) possible autonomic response correlates of behavioral change.

Experiment 1 measured changes in ambient temperature (Ta) selected by highly trained squirrel monkeys during 10-min whole-body microwave exposures at low power densities (2 to 6 mW/cm^2), a range believed to encompass the threshold. Other experiments of comparable duration, but with microwaves absent, constituted control data. Thresholds for a reliable reduction in the Ta normally preferred (when microwaves are absent) were determined for each of four animals, although these behavioral thresholds were different from animal to animal (range = 2 to 4 mW/cm^2) and yielded variable thermoregulatory efficiency. A learning process related to sensory function could have played a role in these findings. Because of the possibility that the threshold might be reduced as the animals became more familiar with exposure at the resonant frequency, a second experiment of this type was conducted in which the power densities were generally lower than 2 mW/cm^2.

Experiment 2 measured changes in Ta selected by the same highly trained squirrel monkeys during 10-min whole-body microwave exposures at very low power densities (0.5 to 2.5 mW/cm^2), a range that overlapped that of Experiment 1. The same control data were again used for comparison. While 2 animals preferred a cooler environment at 1.5 to 2.0 mW/cm^2 during exposure to the resonant frequency, the other two monkeys showed no threshold for reduction of Ta below control levels at any power density in this low range. Analysis shows that the average threshold for alteration of thermoregulatory behavior at the resonant frequency is about 3 mW/cm^2, representing a whole-body SAR of 1.95 W/kg. This value is almost double that determined for the squirrel monkey at 2450 MHz.

Experiment 3 measured steady-state changes in Ta selected by the same highly trained squirrel monkeys during single microwave exposures of 90 minutes duration. The power density was held constant at 5 mW/cm^2 (SAR $\sim$ 3 W/kg). Control data in the absence of microwave exposure were again used for comparison. In addition, the four animals had previously been similarly exposed to 2450 MHz CW microwaves at 20 mW/cm^2 (also 3 W/kg). While the behaviorally-produced Ta and the resulting mean skin temperature in the steady state were virtually identical for the 2 frequencies, colonic temperature was regulated at a significantly higher level during exposure at the resonant frequency than during exposure at 2450 MHz. This result reinforces the conclusion that peripheral thermosensors are inefficiently stimulated by the resonant frequency during behavioral thermoregulation.

Experiment 4 measured transient changes in autonomic thermoregulatory responses (metabolic heat production, peripheral vasodilation, and sweating) that may be manifested in the periphery and may be correlated with changes in thermoregulatory behavior during brief exposures to 450-MHz microwaves. In a constant Ta of 34 °C, four squirrel monkeys underwent brief exposures to

450-MHz CW microwaves at increasing power density (2,4,6,8 mW/cm^2). Vasodilation of the foot or initiation of thermoregulatory sweating occurred at power densities similar to those that had previously been determined as thresholds for the alteration of thermoregulatory behavior. Although causality cannot be proved, the peripheral manifestation of these autonomic responses could have stimulated thermosensors in the skin that had been only inefficiently triggered by direct energy absorption during exposure at the resonant frequency.

The major conclusion drawn from these studies is that thermoregulatory behavior in the presence of the resonant frequency is less effective in regulating the deep body temperature at the normal level than is similar behavior in the presence of higher frequencies. This inconsistency is probably due to two reasons: 1) because the peripheral thermosensors are inefficiently stimulated, and 2) because the deep tissues of the body are heated more efficiently. Autonomic heat loss responses, such as peripheral vasodilation and sweating, are also mobilized during exposure at resonance and, because of their manifestation in the periphery, may aid behavior by auxiliary stimulation of the peripheral thermosensors.

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INTRODUCTION

Standards for human exposure to nonionizing radiofrequency (RF) radiation (17,18,47) reflect the frequency-dependent nature of the rate at which such radiation may be absorbed by biological targets. It is well known that for a given equivalent far-field power density, the specific absorption rate, or SAR, varies widely as a function of body dimensions (21). For any given biological entity, a frequency (or narrow band of frequencies) exists at which the SAR will be maximal. Gandhi has found experimentally that the resonant frequency (under E polarization) occurs approximately when the maximal body dimension is equal to 0.4 of the free-space wavelength of the radiation (24). It is thus extremely important not only to specify the frequency for any experimental investigation of the biological consequences of RF radiation exposure, but also to determine if these consequences may be confirmed at more than the one frequency. Confirming tests, if they can be conducted at the resonant frequency for the organism in question, will serve as a test of the "worst case" in terms of the energy absorbed by the body. It is of note that in the final section of the NCRP report (47), the section that details specific future research needs, a major emphasis is placed on the determination of frequency dependence for observed biological effects. In particular, the NCRP report urged that many more frequencies than 2450 MHz should be employed in the study of thermoregulatory consequences of RF radiation exposure in animal subjects; those frequencies at which the whole body is resonant should particularly undergo investigation (47).

The consequences for thermoregulation of a shift in exposure frequency will not only relate to the whole-body SAR but also directly to the depth to which the radiation penetrates below the skin surface. There are two levels of neural receptors that respond to changes in their own temperature by changes in firing rate, the initial neurophysiological event in the thermoregulatory process. Some thermoreceptors are located in the skin and are primarily responsible for thermal sensations and the initiation of behavioral actions. Residing within 1 mm of the skin surface, these receptors will be stimulated by conventional thermal stimuli in the environment such as radiant or convective heating and convective cooling, but they will also be stimulated by high frequency RF radiation that is absorbed close to the skin surface. On the other hand, other thermoreceptors are located deep in the body, in the brain and spinal cord and in the deep viscera. These receptors normally respond to changes in deep body temperature that are brought about, e.g., during exercise, in febrile disease, and in slowly developing hypothermic and hyperthermic states. Deeply penetrating RF radiation may stimulate these receptors almost to the exclusion of the surface receptors and may also provide very unusual thermal gradients within the body tissues.

While one might anticipate that the thermoregulatory response changes initiated by exposure to RF radiation in a particular environment will depend only upon the rate of whole-body energy absorption, whatever the frequency, unusual thermal gradients generated passively in the tissues must not be discounted. For example, the weak stimulation of surface receptors by deeply penetrating waves will lead to impaired thermal sensation and a potential deterioration of thermoregulatory behavior; these effects may be manifested experimentally by much longer latencies to the initiation of the behavioral selection of a cooler thermal environment by an animal subject. Longer latencies, in turn, will provide more time for increases in deep body temperature before the altered thermoregulatory behavior begins to reverse the process. Whether these effects are merely transitory or persist into the steady state must be determined experimentally.

Energy deposited deep in the body will provide immediate stimulation of the deep thermoreceptors, another unusual physical and physiological event. While one might anticipate that blood flow in the affected region will increase rapidly to dissipate the heat generated (49), there is certainly the possibility for an abnormal stimulation of the receptors in such critical CNS regions as the anterior hypothalamic/preoptic area (presumed site of the "central thermostat" for thermoregulation), posterior hypothalamus, midbrain, medulla, spinal cord and gut. All of these regions figure prominently in the neurophysiological control of thermoregulatory processes in endothermic species. It is certainly possible that increased neural activity in these critical CNS centers may lead to abnormal sequences of thermoregulatory responses, alterations of response hierarchies, and changes in the fundamental thermoregulatory profile of the organism in question. There is no basis in current knowledge for predicting answers to these questions; all must be probed experimentally.

The thermoregulatory profile of an endothermic organism describes the relationship between prevailing ambient conditions and the thermoregulatory response processes available. Figure 1 shows the thermoregulatory profile of the squirrel monkey (the animals used as subjects in these experiments), and illustrates graphically how the principal autonomic responses of heat production and heat loss depend on the ambient temperature (T_a). The responses are considered to be steady state rather than transient, and the air is considered to have minimal movement and water content. Three distinct zones can be defined in terms of the prevailing autonomic adjustment. Below the lower critical temperature (LCT), thermoregulation is achieved by changes in metabolic heat production, other responses remaining at minimal strength. As T_a falls further and further below LCT, heat production increases proportionately. The profile predicts that at cool T_a, EM energy absorbed by an endotherm will spare the metabolic system in proportion to the field strength and will not affect other autonomic responses (8).

At T_a above the LCT, metabolic heat production is at the species-typical resting level, evaporative heat loss is minimal, and thermoregulation is achieved by changes in thermal conductance. Conductance is a measure of heat flow from the body core to the skin and reflects the vasomotor state of the peripheral blood vessels. As vasoconstricted vessels dilate, warm blood is brought from the body core to the surface so that heat may be lost to the environment by radiation and convection. These vasomotor adjustments take place within a species-typical range of T_a called the thermoneutral zone

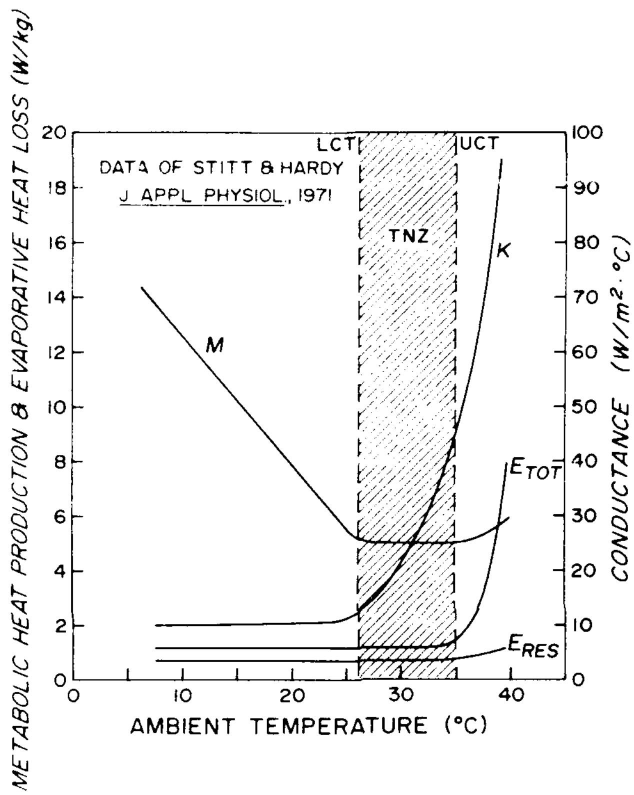


Figure 1. Thermoregulatory profile for the restrained squirrel monkey equilibrated to ambient temperatures ranging from 10 to 39 °C. Individual functions show metabolic heat production (M), total evaporative heat loss (Etot), respiratory evaporative heat loss (Eres), and tissue conductance (K). The thermoneutral zone of vasomotor control (TNZ) encompasses ambient temperatures between the lower critical temperature (LCT) of 26 °C and the upper critical temperature (UCT) of 35 °C. Figure constructed from data of Stitt and Hardy, 1971.

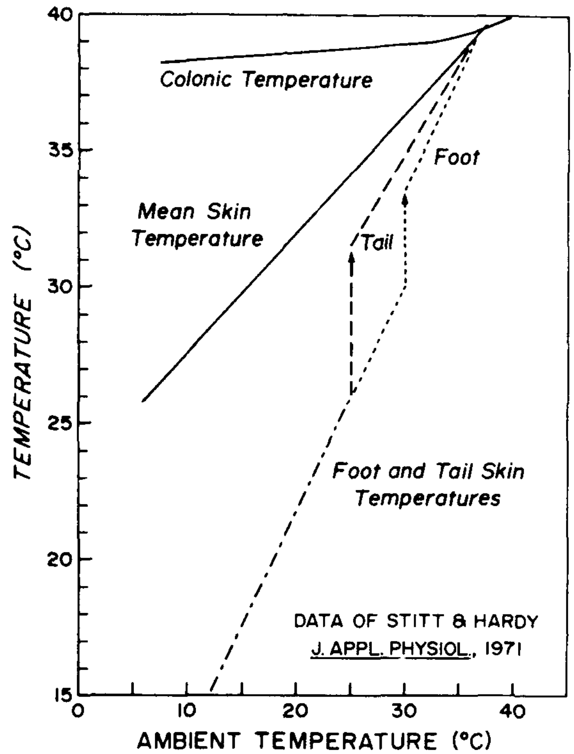


Figure 2. Body temperatures of the restrained squirrel monkey equilibrated to ambient temperature ranging from 10 to 39 °C. Individual functions show deep colonic temperature, mean skin temperature based on four skin sites, and foot and tail skin temperatures. Figure constructed from data in Stitt and Hardy, 1971.

(TNZ). Thus, if an endotherm at thermoneutrality is exposed to RF radiation, augmented vasodilation may occur so that the excess heat generated in deep tissues may be quickly brought to the surface for dissipation to the environment (12,41).

At the upper limit of the TNZ, called the upper critical temperature (UCT), the animal is fully vasodilated and dry heat loss is maximal. A further increase in T_a mobilizes heat loss by evaporation from the skin (sweating) in the case of the squirrel monkey. Man and certain other mammals (e.g., primates) sweat copiously to achieve thermoregulation in hot environments. If squirrel monkeys are exposed to RF fields at T_a above the UCT, their evaporative heat loss will increase in proportion to the field strength (8).

Figure 2 illustrates the relationship between various body temperatures and T_a as measured by Stitt and Hardy (54). Mean colonic temperature (T_{co}) is regulated between 38.5 and 39.8 °C over the range of T_a from 10 to 39 °C. There is a slightly higher rate of increase above the TNZ than below. The mean skin temperature ($\bar{T}_{sk}$) increases linearly with T_a; the slope of the function will be higher when the air in the test compartment is moving, rather than still. Figure 2 also shows dramatic discontinuities in the temperature functions for foot and tail skin. These discontinuities occur at discrete T_a and reflect vasodilation of the peripheral blood vessels of the tail and foot. Warm blood from deep in the body is brought close to the skin surface when these vessels vasodilate, aiding the transfer of metabolic heat to the environment. Changes in vasomotor tonus provide the means for efficient thermoregulation in the squirrel monkey across the entire TNZ. The precise T_a that produce vasodilation of the tail and foot were pinpointed by Lynch et al. who measured steady-state T_{sk} of monkeys restrained in many discrete T_a (43). At T_a of 26.5 °C for the tail and 32 °C for the foot, these local T_{sk} varied widely, indicative of wide variation in local tissue blood flow. Similar results have been reported by Adair and by Adair and Adams (8,12).

It is important to note that any organism may adopt thermoregulatory behavior as an alternate strategy for dealing with the thermalizing effects of exposure to RF radiation. Changes in certain behaviors can alter the physical characteristics of the air-skin interface and thereby maximize the efficiency of heat transfer. Examples are the selection of a more favorable thermal environment, the resetting of a thermostat, and the addition or subtraction of body insulation. These thermoregulatory behaviors also minimize the involvement of autonomic responses of heat production and heat loss, conserve bodily stores of energy and fluid, and produce a state of maximal thermal comfort. Because behavioral responses may be quickly mobilized and are of high gain, they must be considered in any discussion of the thermophysiological consequences of exposure to RF fields. Because they may also be the most sensitive indicators of thermoregulatory response change, behavioral responses are featured in the work described in this report.

Few experimental data relate to the basic problem of the thermoregulatory consequences of near-resonant vs non-resonant RF radiation exposure. The most complete studies to date have been undertaken by Lotz and his colleagues (38,39,40,41,42). All measurements have been made on rhesus monkeys (*Macaca mulatta*) restrained in Styrofoam chairs, sometimes in poorly-controlled thermal environments. Often the studies were designed to determine changes in neuroendocrine responses and had little emphasis on thermoregulation *per se*. Lotz reported in 1985 that excessively high rectal temperatures were measured in monkeys exposed at a frequency (225 MHz) near whole-body resonance compared to an equivalent SAR at a higher frequency (38). Similar results were reported by Krupp who exposed anesthetized rhesus monkeys to 219 MHz RF radiation in an attempt to determine if thermal "hotspots" existed in certain body regions such as wrists and ankles (37). Although Krupp found no evidence for localized regions of greatly-elevated temperature, substantial elevations in rectal temperature were recorded at power levels that had not produced similar elevations during 2.06 GHz exposure (36).

Recent published reports by Lotz and Saxton have determined that restrained, awake rhesus monkeys will reduce an elevated metabolic heat production and initiate vasodilation of the tail in response to both brief and prolonged exposure at 225 MHz microwaves in both 20 and 25 °C environments (40,41,42). These experiments were patterned after those of Adair and Adams conducted on the squirrel monkey (2,12). When the thresholds for response mobilization were compared with those of an earlier study Lotz and Podgorski had conducted at 1.29 GHz, it was found that the lower frequency yielded lower threshold SARs (39). Indeed, Lotz found that despite rapid and orderly response mobilization, substantial increases in rectal temperature occurred during exposure at 225 MHz, even at very low SARs. Unfortunately, these investigators were unable to measure total evaporative heat loss in their animals and so could not determine if they were in thermal balance during the exposures. Although control of the ambient conditions was greatly improved during later studies, there is still some question about the efficiency of heat loss from an animal surrounded by a Styrofoam chair. The major conclusion drawn by Lotz was that during exposure at a near-resonant frequency, hyperthermia occurred at low SARs (equivalent to less than the resting metabolic heat production of the animal), even in a cool environment, and that the thermoregulatory system was somehow overwhelmed by the exposures.

When an endotherm is briefly exposed to RF radiation at a T_a just below the LCT (Fig. 1), the stage is set to initiate the peripheral vasomotor response as soon as metabolic rate has been reduced to the resting level (8). In laboratory animals, the vessels of the tail and ears usually vasodilate before those of the extremities. Generally speaking, once the field strength is sufficient to induce vasodilation (threshold), the response occurs rapidly at field onset and the magnitude or degree of vasodilation is a direct function of the SAR (12,30) or the total heat load (27). Extinction of the RF field induces rapid vasoconstriction. Exposure to infrared fields of comparable intensity fails to induce dilation of the tail in squirrel monkeys, indicating that noncutaneous thermosensors may mediate activation of this thermoregulatory response (12). There is solid experimental evidence that both the threshold and the magnitude of the vasomotor response depend on the imposed frequency (Lotz, personal communication). The closer the frequency to whole-body resonance, the less energy is required to induce vasodilation at a given T_a and the greater the response magnitude at a given SAR.

When the peripheral blood vessels of an endotherm are fully vasodilated, dry heat loss from the body nears its maximum. To avoid significant heat storage and a resultant rise in body temperature, heat loss by evaporation must be initiated. As shown in Figure 1, evaporation occurs when T_a = UCT; it also occurs at T_a within the TNZ during exposure to EM fields at SARs sufficiently high to produce full vasodilation (8).

When the rhesus monkey is exposed to 225-MHz microwaves in thermoneutral environments of 26 and 32 °C, sweating from the calf is reported to occur at SARs close to the equivalent of 80% of the animal's resting heat production (40). In the cooler environment, peripheral vasodilation preceded the onset of sweating, as predicted by the thermoregulatory profile. However, sweating in thermoneutral environments, as with reduced M in cooler environments, failed to prevent a substantial rise in deep body temperature of the rhesus monkey during exposure at the resonant frequency (41).

Very high thresholds have been reported for the initiation of evaporative heat loss in the mouse exposed to a resonant frequency of 2450 MHz (26). In this study, individual mice were irradiated inside an opaque waveguide and the increase in relative humidity of air flowing through the wave guide was taken as the measure of heat lost by the evaporation of body water. Several difficulties accrue from this preparation. When heat stressed, the mouse neither pants nor sweats but is said to increase respiratory frequency somewhat in addition to the spreading of saliva over the fur (28); neither of these responses could be observed. Further, no body temperature could be recorded to provide evidence that the animals were indeed thermoregulating normally. Finally, the ambient temperature during the experiments was 22 °C, well below thermoneutrality for the adult mouse. At this ambient temperature, changes in metabolic heat production, not evaporative heat loss, would be anticipated. It is not surprising, therefore, that the average heat loss "threshold" of 29 W/kg measured in this study -- the equivalent of three times the resting metabolic heat production -- was excessively high.

The results of the studies described above represent about all that we know of changes in thermoregulatory responses in animal subjects during exposure to RF radiation at frequencies near resonance for the species in question. The data are spotty and inconclusive. Only rectal temperature, a few skin temperatures, and, in one published study, metabolic heat production and peripheral vasomotion were assessed. The only information available about changes in thermoregulatory behavior has been published by Gordon (28,29,30,31) for mice and other small rodents moving within a thermal gradient inside an opaque waveguide. While this technique permits minute-to-minute assessments of SAR, neither the environmental temperature selected by the animal, nor the resultant body temperatures, can be measured during microwave exposure, a less-than-satisfactory arrangement. Clearly, this most important question has barely begun to be investigated.

The present report describes initial research designed to determine some of the basic thermoregulatory changes, both behavioral and autonomic, that may accompany both brief and prolonged exposure of squirrel monkeys to the resonant frequency, 450 MHz, in controlled environmental temperatures. The experimental data are compared with extensive data collected on the same species (and in many cases the same animals) at the supraresonant frequency of 2450 MHz and with normative data collected in the absence of RF fields.

THE PROBLEM

The fundamental question addressed in the research reported here is whether the thermoregulatory system of an endotherm may be compromised during exposure to RF radiation at a frequency that is resonant to the whole body. If whole-body SAR is the most important factor, and if the dosimetric studies are of the highest caliber, then the frequency of the radiation employed should matter little. On the other hand, if the pattern of energy deposition in the body is the most important factor and if deep heating in unusual configurations interferes with orderly changes in thermal conductance (i.e., blood flow), then exposure at the resonant frequency may truly be more hazardous than exposure at higher frequencies. Determination of the threshold of activation and exploration of the range of each thermoregulatory mechanism, as well as the modes of interaction between them, will ultimately enhance our understanding of the capability of the whole organism to deal with thermalizing energy deposited deep in the body by RF fields. It is clear that the ambient temperature at which the exposures occur will play a large role in thermal tolerance and will determine the particular ongoing autonomic response or responses at a given time. Using several discrete experimental protocols, similar to those we have employed successfully in the past, we have investigated the thermoregulatory capability, both behavioral and autonomic, of adult male squirrel monkeys exposed whole-body to 450-MHz CW microwaves. In both the design of the experiments and the analysis of the data, we have drawn upon our unique experience with this animal species and the wealth of baseline data collected during the past 21 years on the thermoregulatory consequences of many thermal variables, including exposure to highly regulated microwave fields. Since behavior has historically been demonstrated to be optimally sensitive to imposed RF fields, the research conducted in this project has emphasized changes in thermoregulatory behavior. In our experiments, thermoregulatory behavior is measured by the ambient temperature selected by the animal subject and the efficiency of that behavior by the correlated skin and deep body temperatures. The research reported below has allowed us to:

1. determine the threshold for the alteration of thermoregulatory behavior during brief exposure at the resonant frequency of individual monkeys trained to regulate the temperature of their environment behaviorally;

2. evaluate the importance of exposure duration on the ability to thermoregulate behaviorally;

3. compare behavioral thermoregulation during exposure at the resonant frequency with comparable behavior during exposure at a higher frequency (2450 MHz); and

4. determine the contribution (in terms of whole-body SAR and correlated levels of internal body temperature) of mobilized representative autonomic thermoregulatory responses, peripheral vasodilation, and thermoregulatory sweating, to the initiation of changes in thermoregulatory behavior during exposure to the resonant frequency.

The ultimate goal of research into the biological effects of exposure to RF radiation is to evaluate the impact of comparable exposure on the health and functioning of human beings. Since it is considered morally indefensible to deliberately expose humans to RF fields, it is necessary to use other means to predict potential consequences. One approach might involve the use of sophisticated simulation models of the human thermoregulatory system (56) coupled to a block model of RF energy deposition (25), under the assumption that RF radiation is equivalent to other forms of thermal energy. On the other hand, data derived from animal experiments have been useful in the past and will continue to be an important predictive source, especially if the unique thermoregulatory profile of each species is accounted for (10). The studies reported here have bearing not only upon the promulgation of maximum permissible exposure standards, but also upon the potential consequences of accidental exposure of human beings to RF fields at frequencies resonant to the human body.

METHODS

Subjects

Adult male squirrel monkeys (*Saimiri sciureus*) were used as subjects in these studies. The monkeys' estimated ages ranged from 8 to 18 yr; and their body masses ranged from 850 to 1300 g at the time of testing. The animals were housed individually in a colony room maintained at 24 ±2 °C and 40% ± 10% relative humidity. Water was available ad libitum. The animals were fed a daily ration of Purina monkey chow supplemented with fresh fruit, peanuts, and a milk-pablum mixture. All animals were well adapted to the restraining chair, and most had previously participated in a variety of experiments to assess behavioral and autonomic thermoregulatory capacity. Some of these experiments involved brief exposures to 2450-MHz CW microwave fields at power densities as high as 60 mW/cm^2. The basic procedures for adaptation and chair training were described in Adair et al. (16).

Test Chamber, Dosimetry and Response Measures

A new exposure facility was constructed to provide for exposure of individual squirrel monkeys to 450-MHz CW microwaves at controlled environmental temperatures. A 2.44m x 2.44m x 3.05m (8ft x 8ft x 10ft) chamber was constructed of 19 mm (3/4 in) fir plywood and elevated above the floor on two .31m x .91m x 3.05m (1ft x 3ft x 10ft) wooden boxes. A 1.22m x 1.22m (4ft x 4ft) access door was located in the left wall (Fig. 3). After assembly, the interior surfaces of the chamber were covered with .76 mm (1/32 in) aluminum sheet, stapled in place, on which pyramidal microwave absorber (Advanced Absorber Products, Inc.) was mounted. The receiving wall was covered with 61 cm (24 in) absorbing material (Type AAP-24); the other walls,

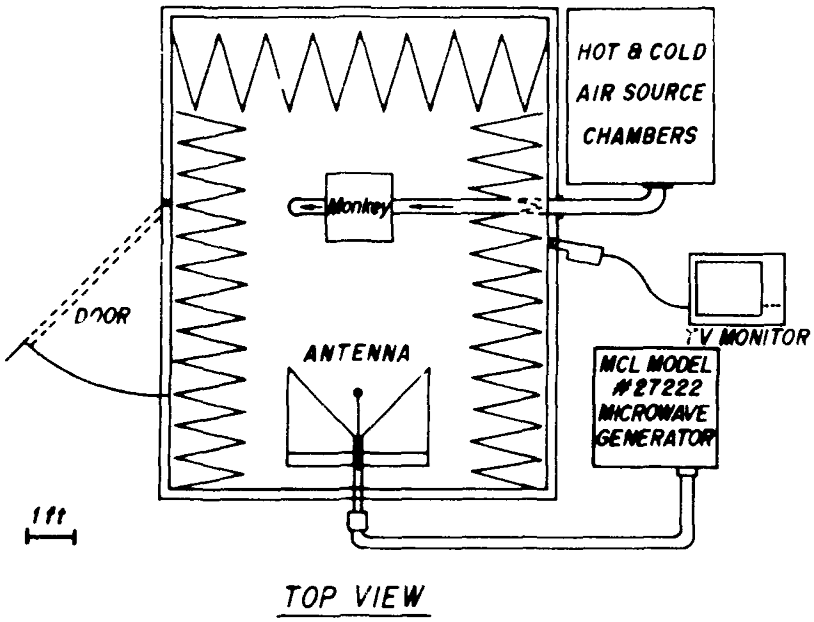


Figure 3. Schematic diagram, as viewed from above, of the anechoic chamber, showing the microwave generator, dipole antenna, and the basic elements in the air control system through the monkey's test compartment. Constant video surveillance of the animal is possible through a window in the test compartment.

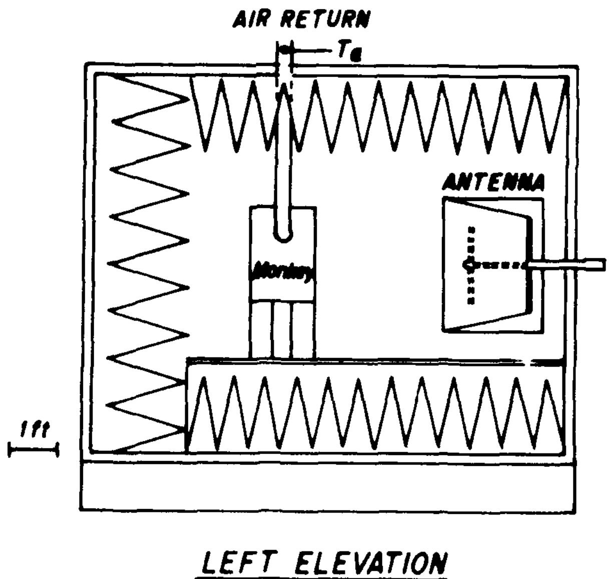


Figure 4. Schematic diagram (left elevation) of the location of the antenna and the animal's test compartment inside the anechoic chamber. Duct for air return and the location of a thermocouple to sense air temperature are also shown.

floor, and ceiling were covered with 46 cm (18 in) absorbing material (Type AAP-18). The central portion of the floor, where the animal's test compartment is located, consists of special solid blocks (Type AAP-18FL) that can be walked on. All absorber was cut to our specifications at the factory. The 46 cm (18 in) pyramidal absorber provides an attenuation of at least 30 dB at 450 MHz.

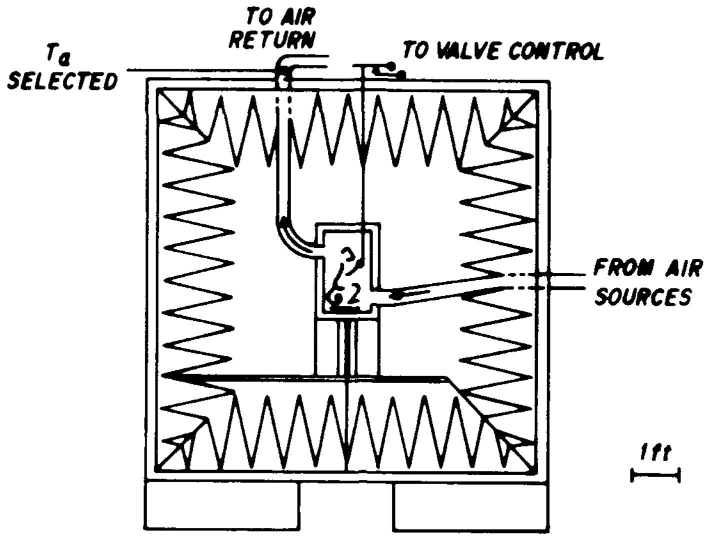
A power source, an MCL Model 15222 variable-frequency Microwave Generator with high voltage power supply and amplifier, was provided for our use by the Radiation Sciences Division at Brooks Air Force Base, TX. The output of this system was 450±2 MHz CW radiation. This source energized a dipole antenna, of length appropriate to propagate 450 MHz waves, mounted within a 90-degree aluminum corner reflector. The location of the antenna inside the chamber, together with the coaxial cable connection to the transmitter, is shown schematically in Figure 3.

Calibration measurements to determine field uniformity at the animal's location were made with a Narda Model 8316B broadband isotropic radiation detector fitted with a Model 8323 probe. This instrument had been recently recalibrated at the factory to both 2450 and 450 MHz. All measurements were made with the Plexiglas stand for the monkey's restraining chair in place on the antenna boresight, 130 cm from the dipole. The probe was held in place by special Styrofoam supports during the measurements; no other instruments were in place in the chamber.

A 50x40-cm plane, centered on the antenna boresight and orthogonal to the direction of propagation of the incident wavefront, was mapped at 10-cm intervals 130 cm from the dipole. This area generously encompassed the area to be occupied by the animal subjects. Power density measurements of the central 20 x 40 cm portion of this plane displayed a 14% nonuniformity at an incident power of 80 watts. An additional 4% nonuniformity was introduced when the Plexiglas restraining chair was present. Measurements of power density along the antenna boresight, at distances from 30 to 130 cm from the dipole and 80 watts incident power, showed a regular decrease as a function of distance from the antenna, with no evidence of standing waves. With the Narda probe placed on the chamber centerline at the location of the monkey's chest, a series of incident powers from 40 to 700 watts yielded a linear function of power density from 1.6 to 22.1 mW/cm^2. Reflected power was nominally less than 0.5% across this range of incident power. Insignificant changes in field measurements occurred with the introduction of a hood and hose connections for measurement of oxygen (O_2) consumption, Vitek probes (Bowman (20)) for measurement of body temperatures, or a Plexiglas boot and hose connections for measurement of thermoregulatory sweating from the foot of the animal. In this regard, Ho (34) has demonstrated that field perturbations produced by such devices may not be as important as other variables (e.g., animal size, configuration and movement, polarization, and uniformity of the incident field).

Serious problems were initially encountered with the attempt to use fine (36-ga) copper-constantan thermocouples to measure some body temperatures, particularly on the skin surface. The recorded thermopotentials exhibited random electrical artifacts that often became more exaggerated as power density was increased. To correct this problem, the wires were shielded by grounded copper tubing run into the anechoic chamber (parallel with the K vector) to within a few centimeters of the monkey's body. The occurrence and magnitude of the artifacts have been greatly reduced by this procedure. Routinely, colonic and brain temperatures are measured with Vitek probes, the thermocouples being used only for measurement of skin temperatures.

An assessment of whole-body energy absorption over the power density range from 5 to 20 mW/cm^2 has been based on temperature increments produced at 3 depths in 2 sizes of saline-filled cylindrical Styrofoam models by 20-min exposures to the radiofrequency field. The mean temperature rise in the liquid above an equilibrated 24° C was used to calculate the specific absorption rate (SAR). The SARs so determined range from 0.750 (W/kg)/(mW/cm^2) for the 0.75 L model to 0.566 (W/kg)/(mW/cm^2) for the 1.1 L model. As reported by Adair (2), conscious squirrel monkeys equilibrated to a thermoneutral T_a can be used as adjunctive dosimeters. The SAR is determined from increments of colonic temperature (T_{co}) during 10-min microwave exposures in animals that are fully vasodilated, but not sweating. Measurements were



VIEW FROM ANTENNA

Figure 5. Schematic diagram (as viewed from the antenna) of the convective system that provides climate conditioning of the animal's test compartment inside the anechoic chamber. Animal controls air temperature by tugging on the cord.

made on four animals, having body masses from 800 to 1300 g, equilibrated to a T_a of 34° C. Ten-min exposures at power densities from 2 to 6 mW/cm^2 yielded SARs ranging from 0.894 to 0.550 $(W/kg)/(mW/cm^2)$, values commensurate with those measured in the saline-filled models. For convenience, an average SAR of 0.65 $(W/kg)/(mW/cm^2)$ has been adopted as representative of absorbed RF energy at 450 MHz for the animals used in the experiments reported here.

During the experiments, the monkey was lightly restrained in a Plexiglas chair in the far field of the dipole antenna within a 30x33x78 cm compartment constructed of 5-cm thick closed-cell Styrofoam. The location of this compartment is shown in Figures 3 and 4. A valve system allowed air from one of two temperature-controlled (±0.5° C) sources to circulate at 0.36 m/s through the compartment in the direction shown in Figure 5. Each monkey was trained to pull a response cord to activate the valves, thereby selecting the T_a preferred. The use of a single air source can provide an environment of closely regulated temperature for the assessment of autonomic thermoregulatory responses. The T_a inside the compartment was sensed by a copper-constantan thermocouple located in the air outlet from the anechoic chamber (Figs. 4, 5) and was recorded continuously on a strip chart and an online computer. The monkey was under constant video surveillance during the 4- to 5-h test sessions. During the experiments, colonic temperature was measured with a Vitek probe and four representative skin temperatures (abdomen, tail, leg, and foot) were measured with fine copper-constantan thermocouples held by special applicators and shielded as described above. Additional refinements of the test environment, unique to each study, will be described in later sections of this report. In general, all data were monitored once a minute by an online computer, plotted immediately and also stored for later analysis.

EXPERIMENT 1: THRESHOLDS FOR ALTERATION OF THERMOREGULATORY BEHAVIOR IN THE PRESENCE OF THE RESONANT FREQUENCY

Introduction

The maintenance of a stable body temperature is essential to the proper functioning of every organism. As discussed earlier, even in those endothermic species that are capable of generating heat in their bodies and that have sophisticated autonomic mechanisms to dissipate that heat to the environment, behavioral responses play an important role. It is far more efficient to reset the thermostat, open a window, or put on a sweater than to take no behavioral action, waiting instead to shiver or to sweat. We have studied thermoregulatory behavior for many years in terms of the ambient temperature (T_a) selected, and presumably preferred, by highly trained experimental animals (16).

Thermoregulatory behavior refers to those voluntary actions by an organism that control the thermal characteristics of the air-skin interface and thereby facilitate regulation of the body temperature at a stable level. Low-intensity microwave fields will influence thermoregulatory behavior as other, more conventional, heat sources do. Rats, trained to press a lever for infrared (IR) heat in the cold, will reduce the rate of lever pressing when a low-intensity 2450-MHz microwave field is present (52). The higher the microwave intensity to which they are exposed (range = 5 to 20 mW/cm^2), the less rats will work for IR heating. We have demonstrated (11) that 10-min whole-body exposures to 2450-MHz CW microwaves, at a power density of 6 to 8 mW/cm^2, reliably alter the thermoregulatory behavior of squirrel monkeys (i.e., stimulate them to select a cooler T_a). Suprathreshold power densities stimulate correspondingly greater reductions in selected T_a and thereby assure regulation of skin and deep body temperatures at the normal level.

Other studies (3,8) have investigated the potential for adaptation of thermoregulatory behavior during prolonged (up to 2.5 h) exposure to 2450-MHz CW microwaves. Three major results have been reported: (1) Whole-body exposure to microwaves at a subthreshold power density (4 mW/cm^2) did not alter thermoregulatory behavior no matter how long it lasted; (2) prolonged exposure at higher power densities, 10 to 45 mW/cm^2, stimulated the monkeys to select T_a from 1.5 to 8.0° C cooler respectively than control levels, ensuring stability of body temperatures; and (3) except for the first microwave presentation of a series or the early minutes of a single long exposure, the length of time the field was on had no significant bearing on the T_a selected or the resulting body temperatures achieved thereby.

The "threshold" power density of 6 to 8 mW/cm^2 for the alteration of thermoregulatory behavior by 2450-MHz CW microwaves represents a SAR (1.2 W/kg) that is the equivalent of about 20% of the resting metabolic heat production (*M*) of the squirrel monkey. Recent experiments (8) have demonstrated that above this threshold value the reduction in preferred T_a is a linear function of the SAR of the imposed field, at least up to a value that is the equivalent of twice the resting *M*. These behavioral changes serve to increase the thermal gradient from body core to skin and from skin to environment, thereby facilitating the loss of heat generated in the body. An additional finding was related to our search for an upper tolerance limit, or "ceiling power density", above which behavioral thermoregulation might break down. For both brief and prolonged whole-body exposure of the squirrel monkey to 2450-MHz CW microwaves, the upper tolerance limit (power density limit) appears to lie above 70 mW/cm^2 under conditions when the animal can exert behavioral control over the temperature of the environment.

Energy from 2450-MHz microwaves during whole-body far field exposure is primarily deposited within 1.5-2.0 cm of the skin surface. The peripheral thermosensors that reside within the outermost 1-mm layer of skin should be efficiently stimulated during such exposure. Furthermore, while the limbs and tail of a squirrel monkey may be heated rather uniformly at this frequency, the head and trunk will not (33). These physical conditions favor efficient thermoregulation, especially via behavioral thermoregulatory responses. At the resonant frequency, however, energy absorbed in deep tissues will promote whole-body hyperthermia, altered thermal gradients within the body tissues, and inefficient stimulation of peripheral thermosensors. As an initial exploration of the effects of the irradiation at the resonant frequency on thermoregulation, Experiment 1 was designed to determine the power density threshold for the alteration of thermoregulatory behavior during brief exposures of the squirrel monkey to 450-MHz CW microwaves.

Methods and Procedure

Adult, male squirrel monkeys (Saimiri sciureus) were used as subjects in all experiments reported here. They were individually housed in a vivarium maintained at 24±2 °C with free access to water, and with a daily ration of Purina Hi-Pro Monkey Chow that was supplemented with a milk-cereal mixture, fresh fruit, peanuts and vegetables. Prior to these studies, each animal had been trained to regulate T_a behaviorally, and all had previously been extensively exposed to 2450-MHz microwave fields under a variety of experimental protocols. The body masses of the animals used in Experiment 1 ranged from 800 to 1000 g.

In Experiment 1, four squirrel monkeys underwent brief (10-min) whole-body exposures to 450-MHz CW microwaves (E-polarization) at incident power densities that ranged from 2 to 6 mW/cm^2, while controlling T_a behaviorally. During the experiments, individual animals were lightly chair-restrained inside a Styrofoam compartment that was ventilated by a temperature-controlled airstream (Fig. 5). Each animal was trained to pull a cord to select between two preset T_a, 10 and 50 °C. The monkey was exposed to air at 10 °C and each response was reinforced by a 15-s presentation of air at 50 °C. Air at the original temperature then automatically returned until the monkey responded again. In the absence of microwaves, all animals selected an average T_a of 35-36 °C. The selected T_a was measured by a copper-constantan thermocouple in the air outlet from the anechoic chamber (Fig. 5) and recorded continuously on both a strip chart and online computer.

During the experiments, colonic temperature (T_{co}) and the temperatures of four representative skin areas (tail, leg, abdomen, and foot) were read once a minute by an online computer. T_{co} was measured by the probe of a Vitek Electrothermia Monitor (20) inserted 10 cm past the anal sphincter. To measure the skin temperatures, thermocouples with 0 °C reference junctions were constructed in special configurations from 36-ga copper-constantan wire. The leads were shielded by grounded copper tubing aligned with the K-vector (see above) and the hot junctions were held out of alignment with the E-field vector of the incident planewave to minimize field effects. Any measured skin temperature (T_{sk}) that showed abrupt changes greater than 0.2 °C (equivalent to an electromotive force [emf] change greater than 8 microvolts) correlated with microwave onset or termination was discarded or corrected on the basis of readings taken when no microwaves were present. From the four T_{sk}, a weighted mean skin temperature ($\bar{T}_{sk}$) was calculated (Stitt, et al., 1971):

$$\bar{T}_{sk} = 0.11T_{tl} + 0.37T_{lg} + 0.45T_{abd} + 0.07T_{ft}.$$

Each experimental session lasted 4 to 5 h, and always began with a 2-h period with no microwaves present to stabilize thermoregulatory behavior and all measured body temperatures. Following the initial stabilization period, a series of five 10-min microwave exposures in an ascending order of power density (2, 3, 4, 5, and 6 mW/cm^2) was presented. A 10-min period with no microwaves present was allowed between successive exposures to restore the air and body temperatures to normal levels. A 30-min period of behavioral thermoregulation (microwaves absent) terminated the session. Five experimental sessions on each of four squirrel monkeys were conducted. No animal served as a subject more often than once per week. To serve as comparison (control) data, five 4-h sessions of behavioral thermoregulation in the absence of microwaves were conducted on each monkey. So that the responses of animals measured in the presence of 450-MHz microwaves could be compared with previously-reported results at 2450 MHz, control data, using the same protocol, were collected on the four monkeys in our 2450-MHz exposure facility.

Results

The data from all experiments were analyzed for each animal individually; thus, each animal served as its own control. Mean values (± 1 SEM) of each measured dependent variable were computed for each 10-min segment of each

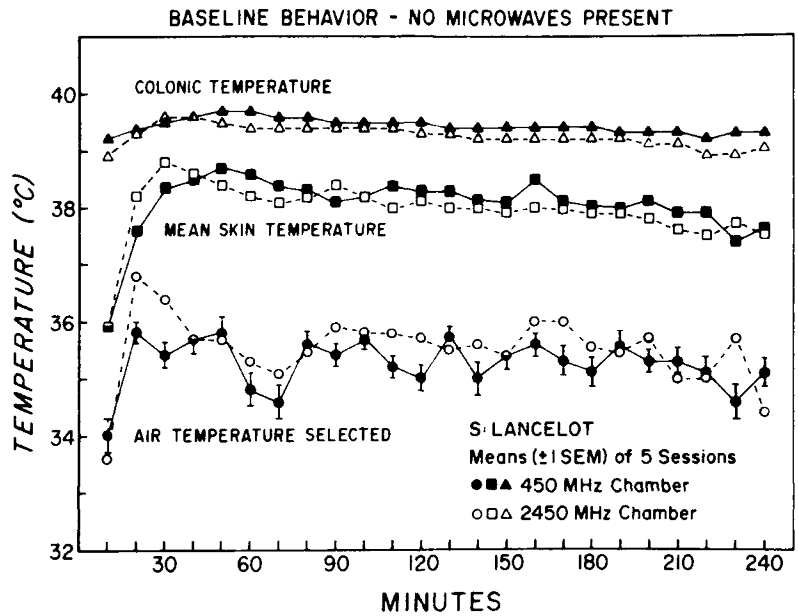


Figure 6. Normal thermoregulatory behavior, exhibited by one monkey (S:LANCELOT) in the absence of microwaves, in both the 2450-MHz (open symbols) and 450-MHz (closed symbols) exposure test environments. Each data point represents means (± 1 SEM) of the preceding 10 minutes averaged across 5 test sessions.

experiment across the five experiments in each series. The T_a selected by the animal was determined from air outlet temperature (T_a in Fig. 5). For this purpose, the stripchart record of airstream temperature was digitized at 1-min intervals.

At the outset, it was important to verify the similarity of the behavioral selection of preferred T_a in the two exposure environments, the 450-MHz exposure chamber and the 2450-MHz exposure chamber. Theoretically, small differences in source temperature control, air velocity, system response time, and programming contingencies could yield slightly different behavioral patterns and body temperatures. The mean T_a (± 1 SEM) selected by one monkey (solid circles), together with the T_{co} (solid triangles) and $\bar{T}_{sk}$ (solid squares) in the 450-MHz exposure chamber are shown in Figure 6, together with their counterparts measured in the 2450-MHz exposure chamber (open symbols). Both data sets represent control series of five experimental sessions when no microwaves were present. The SEMs are not shown for the T_{co} and $\bar{T}_{sk}$ because they were smaller than the symbols used to plot the mean data. There is no reliable difference between the two data sets that can be attributed to the exposure environments; that is, the T_a selected and the resulting body temperatures are the same in the two exposure environments when microwaves are absent. Data for the other monkeys, tested in both exposure chambers, were identical to those presented in Figure 6. Thus, in terms of normal thermoregulatory behavior, the two exposure systems yield virtually identical behavioral and thermal data.

Figure 7 shows results (solid symbols) from a single, early experiment on one monkey exposed for five 10-min periods to 450 MHz CW microwaves at increasing power density, compared with mean control data (microwaves absent) collected in five experiments in the 450-MHz exposure chamber (open symbols). This early experiment to determine the power density threshold for the alteration of thermoregulatory behavior during 450-MHz exposure appeared to show a preference for a cooler environment than normally selected at power densities of 5 mW/cm^2 and above. However, a later experimental session (Fig. 8) shows a possible threshold at a power density as low as 2 mW/cm^2 (compared to the mean control data), a body temperature regulated at a lower level than

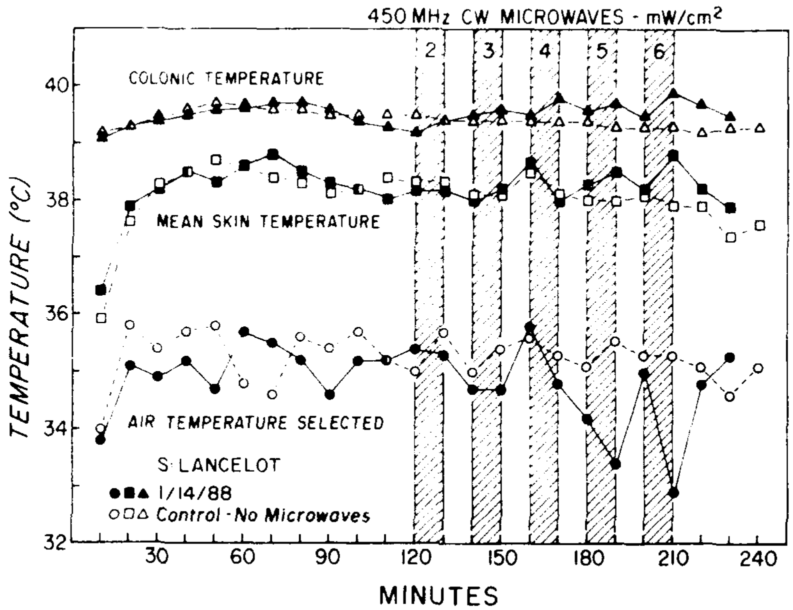


Figure 7. Representative experiment on one monkey (S:LANCELOT) (solid symbols), compared with control data (open symbols), to determine the threshold for alteration of thermoregulatory behavior by 450-MHz CW microwaves. Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

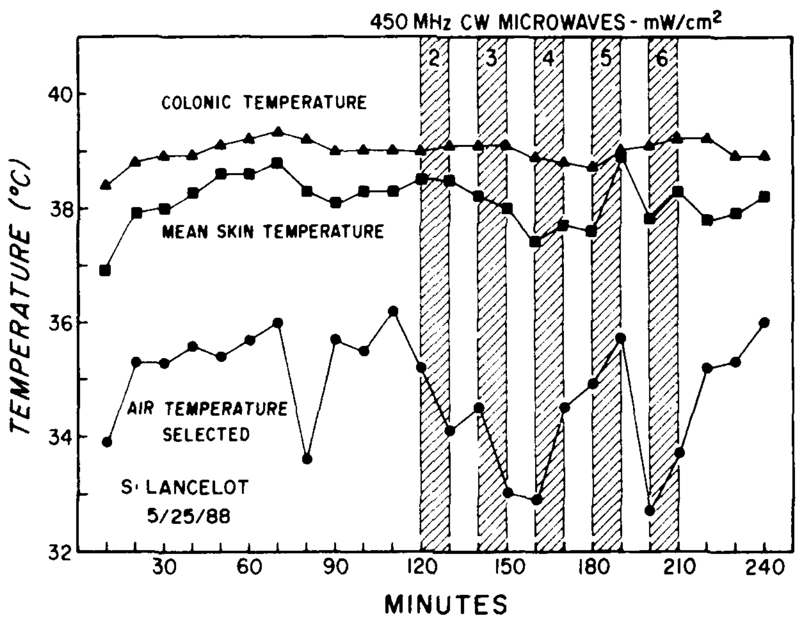


Figure 8. Single experiment on one monkey (S:LANCELOT) to illustrate erratic behavioral thermoregulation during 10-min exposures to 450-MHz CW microwaves. Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

normal, but far greater variability in the response measures than is shown in Figure 7. These data illustrate a singular finding of this experiment: that excessive variability was very characteristic of the behavioral thermoregulatory responses to exposure at the resonant frequency. All of the four monkeys exhibited highly variable responses that did not improve markedly with practice. Observation of individual animals (via video) during each session led to the impression that the animals were confused by the stimuli presented. This impression was underwritten by data that featured long response latencies and inconsistent behavioral patterns. In general, the data seemed far more variable than the threshold data at 2450 MHz collected many years earlier using identical protocols.

Figures 9 through 12 show, for each of the test animals, the mean T_a selected, ± 1 SEM (solid circles), together with the resulting mean T_{co} (solid triangles) and $\bar{T}_{sk}$ (solid squares), measured during five experiments in which the animals were exposed for 10-min periods to 450-MHz CW microwaves at increasing power density (hatched regions). Comparable data collected during five control experiments, when microwaves were absent, are shown in open symbols. Each plotted symbol represents the mean value calculated over the preceding 10-min period. In general, the SEM for means of T_{co} and $\bar{T}_{sk}$ were smaller than the symbols used to plot the data.

The purpose of this experiment was to determine a threshold power density at and above which squirrel monkeys would reliably select a cooler environment than normally preferred. Student's T-test was used to determine the reliability of the difference between the mean T_a selected during the 10-min microwave exposure at each power density and the comparable 10-min period during the control experiments when no microwaves were present; a P-value of .05 or greater indicated statistical significance between the means. Thus, for S:Lancelot (Fig. 9), the threshold was 5 mW/cm^2 ($P<.05$); although the means at 3 mW/cm^2 also differed significantly ($P<.05$), those at 4 mW/cm^2 did not. Thresholds for the other three monkeys were similarly determined to be 2 mW/cm^2 for S:Kipp (Fig. 10), 4 mW/cm^2 for S:Whitehead (Fig. 11), and 4 mW/cm^2

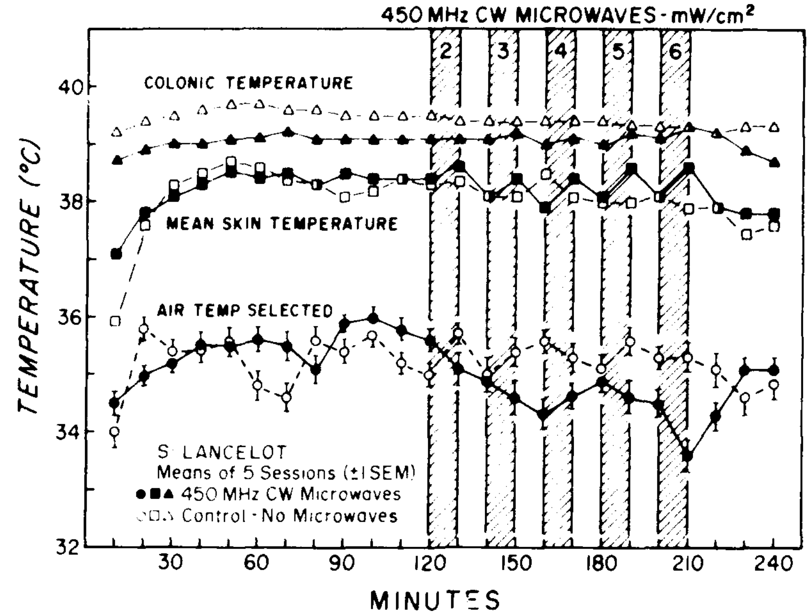


Figure 9. Behavioral thermoregulation (S:LANCELOT) during brief whole-body exposures to 450-MHz CW microwaves at increasing power density (solid symbols) compared with control data when microwaves were absent (open symbols). Each data point represents means (± 1 SEM) of the preceding 10 minutes averaged across 5 test sessions. Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

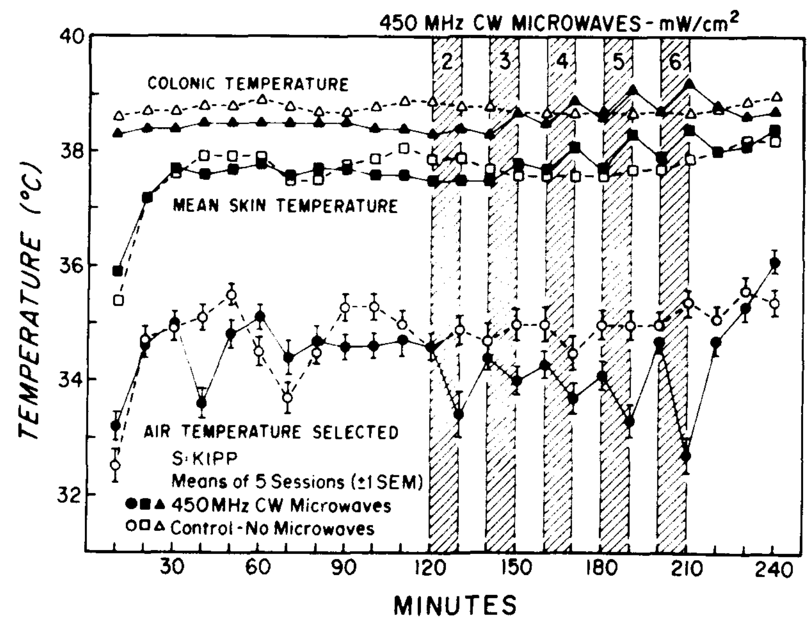


Figure 10. Behavioral thermoregulation (S:KIPP) during brief whole-body exposures to 450-MHz CW microwaves at increasing power density (solid symbols) compared with control data when microwaves were absent (open symbols). Each data point represents means (± 1 SEM) of the preceding 10 minutes averaged across 5 test sessions. Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

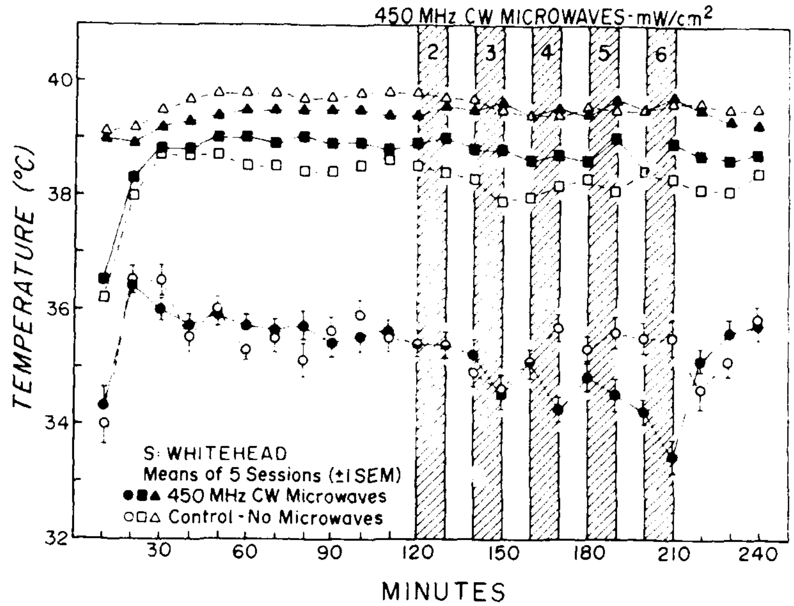


Figure 11. Behavioral thermoregulation (S:WHITEHEAD) during brief whole-body exposures to 450-MHz CW microwaves at increasing power density (solid symbols) compared with control data when microwaves were absent (open symbols). Each data point represents means (± 1 SEM) of the preceding 10 minutes averaged across 5 test sessions. Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

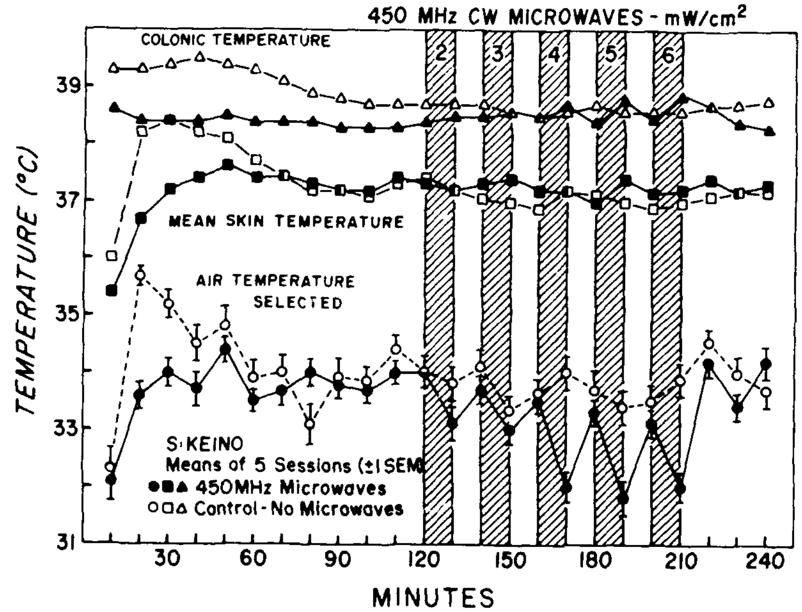


Figure 12. Behavioral thermoregulation (S:KEINO) during brief whole-body exposures to 450-MHz CW microwaves at increasing power density (solid symbols) compared with control data when microwaves were absent (open symbols). Each data point represents means (± 1 SEM) of the preceding 10 minutes averaged across 5 test sessions. Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

r S:Keino (Fig. 12). Based on our dosimetry, these thresholds represent a SAR range from 1.3 to 3.25 W/kg.

In general, during most of the 10-min periods when the RF field was present, the test animals selected a cooler T_a than they had during the previous 10-min period which is particularly evident in the data of S:Kipp (Fig. 10) and S:Keino (Fig. 12). The sole exceptions were RF exposure at 4 mW/cm^2 for S:Lancelot (Fig. 9) and 2 mW/cm^2 for S:Whitehead (Fig. 11). Thus, were it not for the variability in mean T_a selected during the control sessions (RF absent) the calculated thresholds might have been considerably lower.

However, selection of a cooler T_a during RF exposure did not necessarily yield stable skin and deep body temperatures. Three of the four animals sustained higher-than-normally preferred mean skin temperatures when the RF field was present, especially at power densities above 4 mW/cm^2. Two animals sustained minimal increments in T_{co}, even at a power density of 6 mW/cm^2 (Figs. 9, 11). On the other hand, the T_{co} of the other two animals was elevated by as much as 0.5 °C during RF exposure at the higher power densities, despite significant behavioral reductions in T_a (Figs. 10, 12). In general, those monkeys that exhibited the most appropriate behavioral change achieved the least effective thermoregulation thereby. There was no positive correlation between T_{co} elevation and either body mass or any other physical characteristic of individual animals. However, the two monkeys that achieved the best regulation of deep body temperature had many more years of experience with exposure to RF fields (primarily 2450 MHz) than the other two monkeys.

Discussion and Conclusions

A standardized protocol that we have used successfully in the past to determine RF thresholds for changes in behavioral thermoregulation was employed in Experiment 1. This protocol involved stabilization of thermoregulatory behavior for 2 h, followed by a series of 10-min exposures to the RF field, at increasing power density, separated by 10-min periods of restabilization. Always before, we had exposed our experimental animals to

2450-MHz CW radiation, under conditions of both whole- and partial-body exposure. The present experiment marked the first time any of our squirrel monkeys had experienced exposure at another frequency, viz the resonant frequency of 450 MHz. Over the course of five test sessions in Experiment 1, all animals exhibited purposeful alterations in thermoregulatory behavior (i.e., selection of a cooler T_a when the RF field was present) that was closely related to the strength of the incident field. However, the detailed character of the behavioral response pattern and the resulting changes in skin and deep body temperatures were quite different from those we had observed over many years of experimentation with 2450-MHz CW microwave fields (3,5,8,10,11,14,15).

The fact that all monkeys selected a cooler T_a than their current preference, nearly every time the RF field was turned on, was provocative even though the statistically-determined thresholds for response change were at considerably higher field strengths. This finding suggested that perhaps the lowest field strength employed in this series (2 mW/cm^2, representing a whole-body SAR of 1.3 W/kg) was close to the true "threshold" for the alteration of thermoregulatory behavior. Our earlier studies at 2450 MHz had indicated that the optimal stimulus range for threshold determinations encompassed the true threshold (11,14) and that spurious response changes could often accompany the initial RF presentation of a series, whatever its magnitude (4,5,6,14).

The dissimilar effect on thermoregulation of the various behavioral response strategies exhibited by the four squirrel monkey subjects in Experiment 1 was also disquieting, coupled with our analysis that the most practiced individuals exhibited "uncharacteristic" behavior, yet more efficient regulation of deep body temperature. The less experienced subjects tended to regulate their skin temperatures somewhat more efficiently at the expense of slight hyperthermia (i.e., ΔT_{co} as high as 0.5 °C). Clearly, the difference in energy absorption from the two frequencies (2450 and 450 MHz) was affecting behavioral thermoregulatory responses in unusual ways that required more detailed experimental analysis.

The two parameters of the independent variable (450 MHz RF radiation exposure) that are most pertinent to this analysis are its intensity and its duration. Because the results of Experiment 1 indicated that the "threshold" for alteration of the behavioral response might have been as low as 2 mW/cm^2, the lowest power density presented in the series, it was clear that additional experimental sessions should be conducted. These sessions should employ the same protocol, but involve a range of power densities considerably below those explored in Experiment 1. This strategy would be certain to encompass the true "threshold" for alteration of the behavioral response.

Previous studies of behavioral thermoregulation in the presence of RF fields have indicated that there may be a considerable latency between field onset and initiation of behavioral action (8,9,10,14,15). Certainly, considerable time (e.g., up to 30 min) may be required for the establishment of steady-state behavioral responding in the face of prolonged RF exposure (8). The inefficient stimulation of surface thermoreceptors by absorbed energy at the resonant frequency could exacerbate the latency problem and contribute to variable measures of response thresholds for relatively brief exposures, such as those observed for the 10-min exposures used in Experiment 1. Therefore, it is important to determine the time course of behavioral thermoregulation in the presence of resonant RF fields of prolonged duration. Such experiments would yield more accurate measures of the pertinent dependent variables in the steady-state: T_a selected and the resulting skin and deep body temperatures. On the basis of this evaluation, Experiment 2 was designed to probe the question of stimulus intensity, and Experiment 3 the question of stimulus duration.

EXPERIMENT 2: BEHAVIORAL THERMOREGULATION IN THE PRESENCE OF VERY LOW INTENSITY IRRADIATION AT THE RESONANT FREQUENCY

Introduction

The results of Experiment 1 had been equivocal: while statistical evaluation of the "threshold" for the alteration of thermoregulatory behavior during 10-min exposures to 450-MHz fields had yielded values from 2 to 5 mW/cm^2, the test animals in that experiment had nearly always selected a cooler environment whenever the RF field was present, relative to that preferred immediately before exposure. The statistically-derived "threshold" compared the mean T_a selected under 10-min of RF exposure with the mean T_a selected at a comparable time period of the control (RF absent) experiments. It appeared prudent to explore a series of power densities that were lower than, but also overlapping, those used in Experiment 1 to determine the "true" threshold for the alteration of thermoregulatory behavior by the four squirrel monkey subjects of Experiment 1. This experimental strategy has been employed to advantage several times in the past (8,9,11,14). Use of the same animal subjects and an identical protocol (except for the specific power densities investigated) meant that the data from the two experiments could be pooled and the aggregate analyzed statistically. Further, the control experiments (RF absent) which had already been conducted on each animal could again serve as normative data for statistical analysis.

Methods and Procedure

The same four squirrel monkeys served as subjects in Experiment 2. All had shown modest weight gain (range = 875 to 1100 g) since the first experiment. Housing and feeding regimes had not changed.

The apparatus, response measures, and basic experimental protocol were identical to those described under Experiment 1 with the sole exception of the power density range explored. In Experiment 2, the range of power densities was 0.5 to 2.5 mW/cm^2, always presented in ascending order. It has been demonstrated that the order of stimulus presentation in such experiments is an

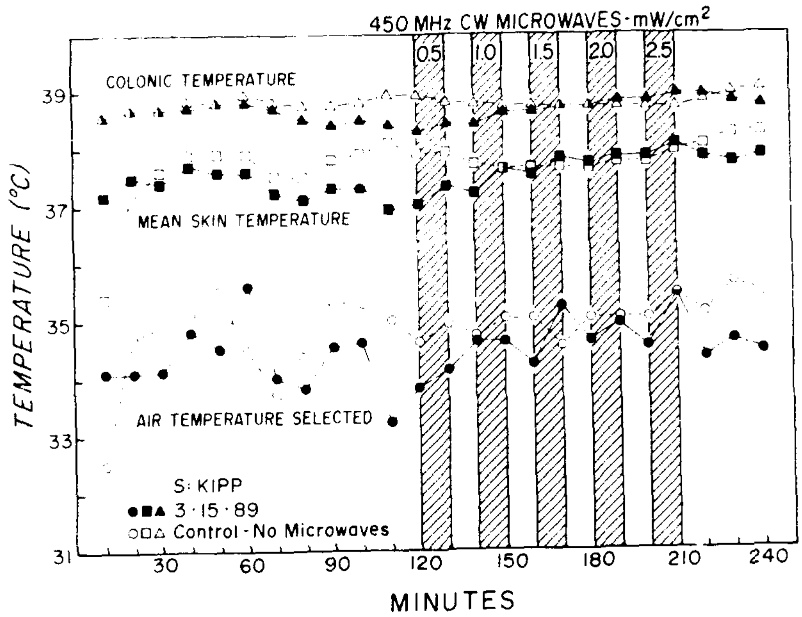


Figure 13. Representative experiment on one monkey (S:KIPP) (solid symbols), compared with control data when no microwaves were present (open symbols), to determine threshold for alteration of thermoregulatory behavior by brief exposures to 450-MHz CW microwaves at very low power density (0.5 to 2.5 mW/cm^2). Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

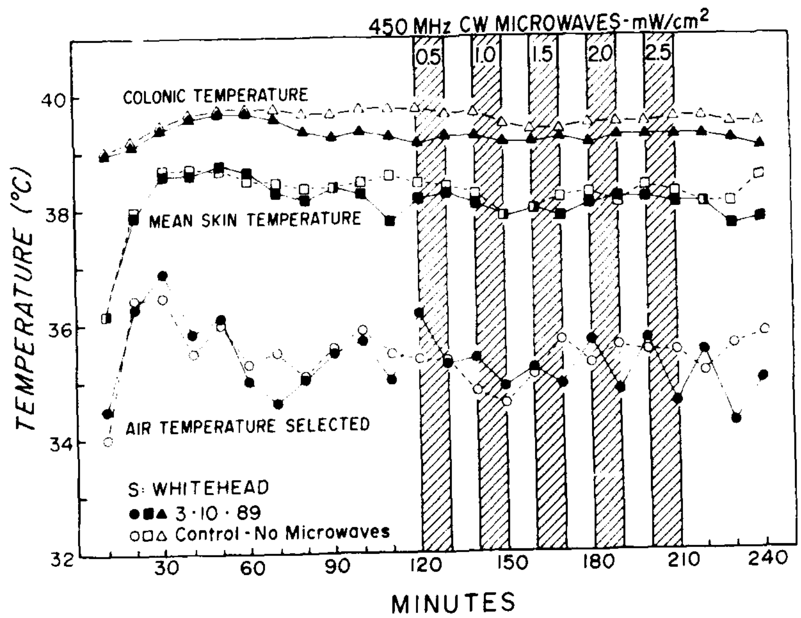


Figure 14. Representative experiment on one monkey (S:WHITEHEAD) (solid symbols), compared with control data when no microwaves were present (open symbols), to determine threshold for alteration of thermoregulatory behavior by brief exposures to 450-MHz CW microwaves at very low power density (0.5 to 2.5 mW/cm^2). Individual functions show air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

insignificant variable (8). As in Experiment 1, each experimental session began with a 2-h period for stabilization of thermoregulatory behavior and all body temperatures followed by five 10-min exposures to 450-MHz CW microwaves at power densities of 0.5, 1.0, 1.5, 2.0, and 2.5 mW/cm^2, separated by 10-min restabilization periods. A 30-min period of behavioral thermoregulation (RF absent) terminated the session. Five such experimental sessions were conducted on each of the four monkeys.

Results

The data from Experiment 2 were analyzed in identical fashion to those from Experiment 1. Mean values (± 1 SEM) of each measured dependent variable were computed for each 10-min segment of each session across the five experimental sessions for a given animal. The T_a selected by the animal was again determined from the temperature recorded at the air outlet, digitized at 1-min intervals.

Figures 13 and 14 show typical results (solid symbols) in single experimental sessions for two different monkeys in which the animals were exposed for five 10-min periods to 450-MHz CW microwaves at increasing power density (0.5 to 2.5 mW/cm^2). The open symbols represent mean control data collected in five sessions conducted in the 450-MHz chamber with no microwaves present.

The data displayed in the two figures illustrate two types of responses observed in this experiment. The animal whose data are shown in Figure 13 exhibited random changes in thermoregulatory behavior when the RF field was present; overall, the T_a selected and the resultant skin and deep body temperatures were not different from the control data shown in open symbols. Although mean skin temperature gradually rose during minutes 120 to 210 of the session, this rise was caused primarily by selection of a warmer T_a by the animal while the RF field was present. On the other hand, Figure 14 shows behavioral responses more like those recorded in Experiment 1, i.e., a reduction in T_a whenever the RF field was present. It is not clear from this single experiment whether a "threshold" for behavioral change was attained,

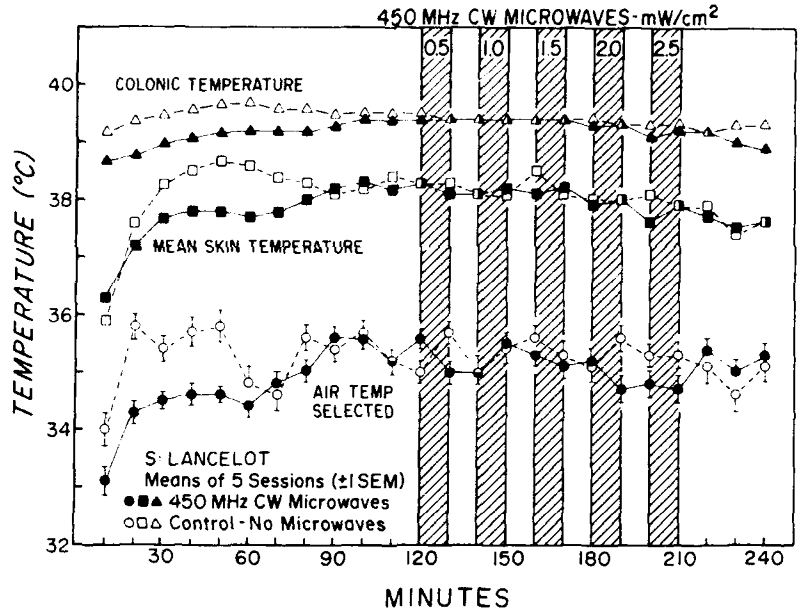


Figure 15. Behavioral thermoregulation (S:LANCELOT) during brief whole-body exposures to 450-MHz CW microwaves at very low power density (closed symbols) compared with control experiments when microwaves were absent (open symbols). Each data point represents the mean (± 1 SEM) of the preceding 10 min averaged across 5 experimental sessions. Individual functions show mean air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

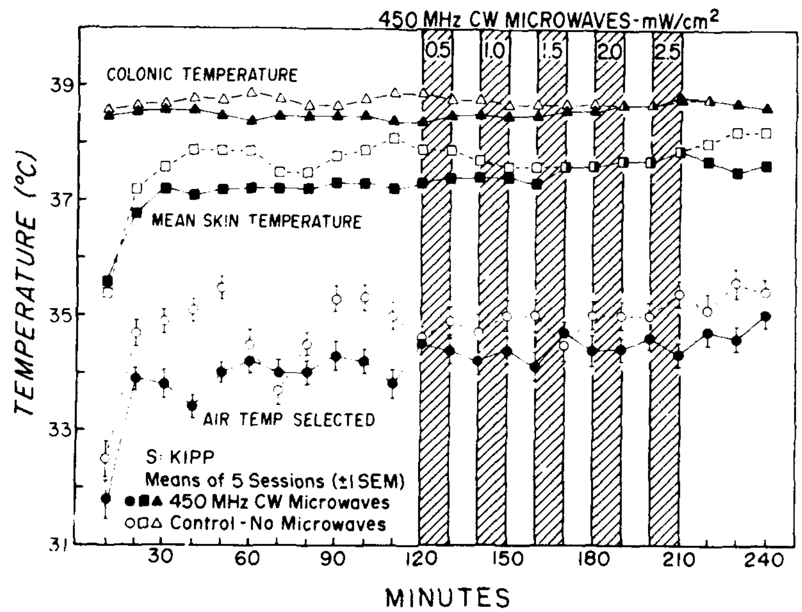


Figure 16. Behavioral thermoregulation (S:KIPP) during brief whole-body exposures to 450-MHz CW microwaves at very low power density (closed symbols) compared with control experiments when microwaves were absent (open symbols). Each data point represents the mean (± 1 SEM) of the preceding 10 min averaged across 5 experimental sessions. Individual functions show mean air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

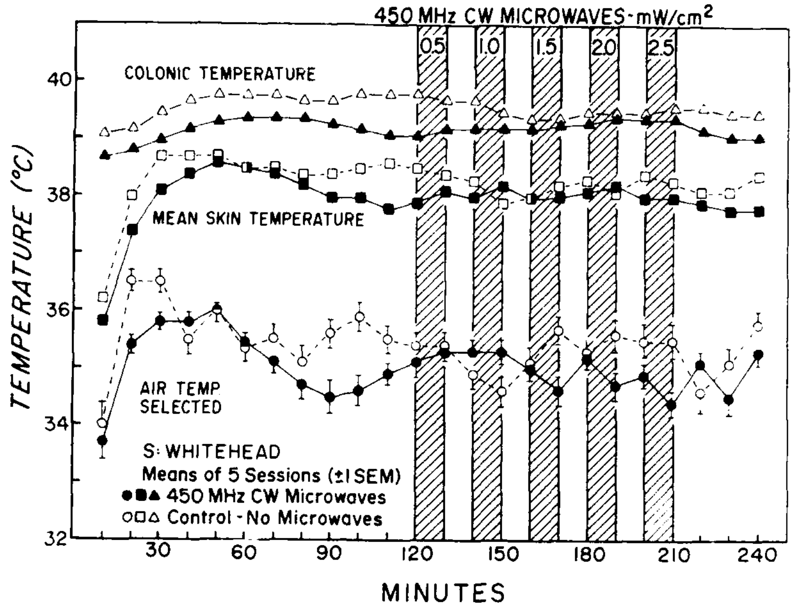


Figure 17. Behavioral thermoregulation (S:WHITEHEAD) during brief whole-body exposures to 450-MHz CW microwaves at very low power density (closed symbols) compared with control experiments when microwaves were absent (open symbols). Each data point represents the mean (± 1 SEM) of the preceding 10 min averaged across 5 experimental sessions. Individual functions show mean air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

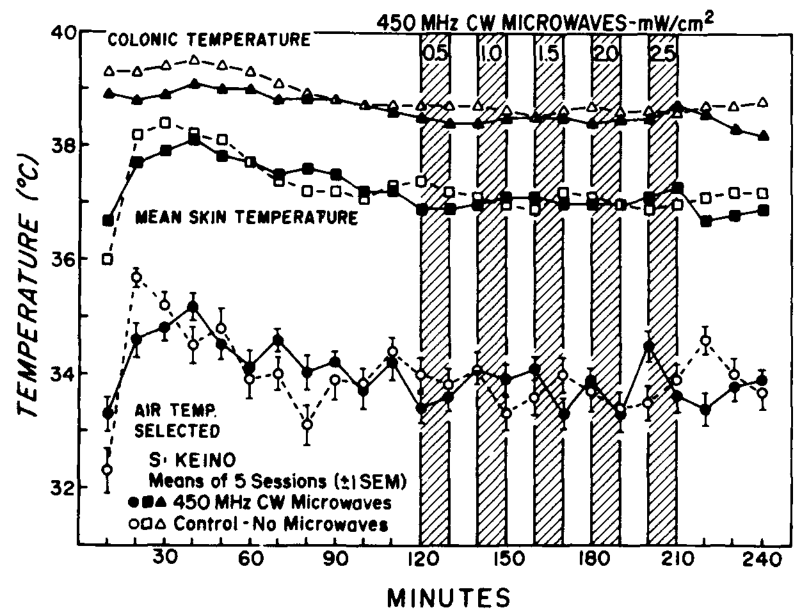


Figure 18. Behavioral thermoregulation (S:KEINO) during brief whole-body exposures to 450-MHz CW microwaves at very low power density (closed symbols) compared with control experiments when microwaves were absent (open symbols). Each data point represents the mean (± 1 SEM) of the preceding 10 min averaged across 5 experimental sessions. Individual functions show mean air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

although the T_a preferred appeared to be substantially below control levels when power density was 1.5 mW/cm^2 and above. Throughout the experimental session, both $\overline{T}_{sk}$ and T_{co} were regulated efficiently at control levels.

Figures 15 through 18 show, for each of the test animals, the mean T_a selected ± 1 SEM (solid circles), together with the resulting mean T_{co} (solid triangles) and $\overline{T}_{sk}$ (solid squares), measured in five experiments in which the animals were exposed for 10-min periods to 450-MHz CW microwaves at increasing power density (hatched regions). Comparable data collected during five control experiments, when microwaves were absent, are shown in open symbols. Each plotted symbol represents the mean value calculated over the preceding 10-min period. In general, the SEMs for means of $\overline{T}_{sk}$ and T_{co} were smaller than the symbols used to plot the data.

As in Experiment 1, Student's T-test was performed to determine the reliability of the difference between the mean T_a selected during the 10-min microwave exposure at each power density and the comparable 10-min period during the control experiments when no microwaves were present. A P value of at least .05 indicated statistical significance between the means. These tests were conducted to determine the threshold power density at and above which the monkeys reliably selected a cooler environment than normally preferred. For S:Lancelot (Fig. 15), no threshold was determined across the power density series of Experiment 2; although the T_a means at 2 mW/cm^2 differed significantly ($P<.05$), those at 2.5 mW/cm^2 did not. Thresholds for the other three monkeys were similarly determined to be 2 mW/cm^2 for S:Kipp (Fig. 16), 1.5 mW/cm^2 for S:Whitehead (Fig. 17), and no threshold for S:Keino (Fig. 18). Comparison of these thresholds with those determined for the same animals in Experiment 1 revealed that for only S:Whitehead was there a discrepancy: 4 mW/cm^2 in Experiment 1 vs 1.5 mW/cm^2 in Experiment 2. The threshold of 2 mW/cm^2 for S:Kipp was the same in both experiments, while lack of a reliable threshold determination in Experiment 2 for S:Lancelot and S:Keino indicated that the Experiment 1 determinations of 5 and 4 mW/cm^2, respectively, were preserved. Based on our dosimetry, this expanded range of power density "thresholds" represents a SAR range from 0.97 to 3.25 W/kg. The median power density of all threshold determinations was 3 mW/cm^2 (SAR=1.95 W/kg), which is probably most representative of this diverse sample. There seems no obvious alternate statistical solution although a graphical solution is attempted below.

Examination of Figures 15-18 reveals that for no monkey was there any difference in the regulated mean T_{co} or mean $\bar{T}_{sk}$ from control levels that could be attributed to 10-min exposure of the animals to 450-MHz fields. The field strengths in this series may have been of insufficient magnitude to cause measureable heating of body tissues. It is also possible that such changes in thermoregulatory behavior that did occur were sufficient to counteract any slight tissue heating.

Combined Data from Experiments 1 and 2

In order to combine the results from the first two experiments, additional simplification of the data was undertaken. The results are summarized for one monkey (S:Lancelot) in Figure 19 for the total power density range of 1.5 to 6 mW/cm^2 covered by the two experiments. The bullseyes plotted at a power density of 0 mW/cm^2 represent the mean T_{co}, $\bar{T}_{sk}$ and T_a selected during the final 30 min of the baseline stabilization periods when no microwaves were present. The other symbols, coded in terms of the two experimental series, represent mean temperatures calculated across five experimental sessions during the 10-min periods when microwaves were present. The combined data for this monkey show that there is a gradual reduction of 2 °C in T_a selected across this range of power densities, but no notable change in either T_{co} or $\bar{T}_{sk}$.

Similar analyses for the other three monkeys appear in Figures 20, 21, and 22. T combined data for S:Kipp (Fig. 20) show a gradual reduction of 1.7 °C in T_a selected across the range of power densities explored that was accompanied by a gradual elevation in $\bar{T}_{sk}$ and T_{co} of about 0.8 °C. The combined data for S:Whitehead (Fig. 21) also show a gradual reduction of 1.8 °C in T_a selected, but more modest accompanying elevations of $\bar{T}_{sk}$ and T_{co}. The analysis for this animal is complicated by the fact that the regulated

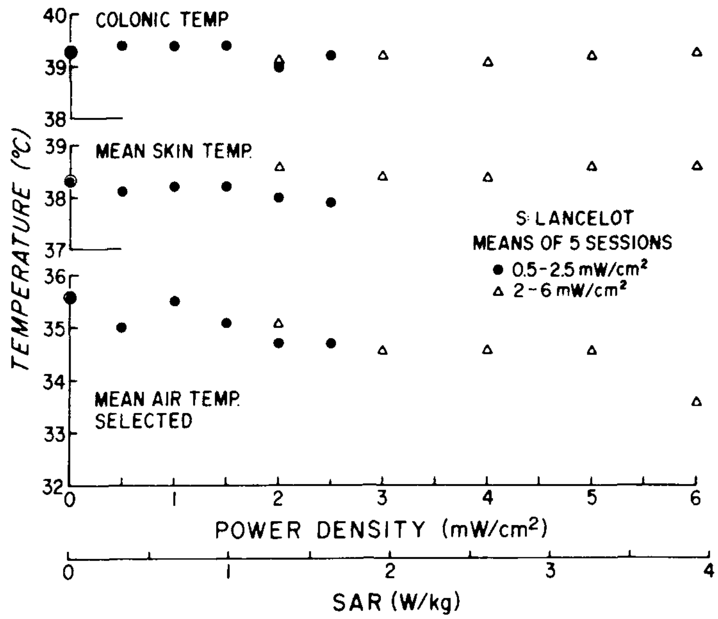


Figure 19. Summary of data from Experiments 1 and 2 (S:LANCELOT) covering power density range from 0 (control) to 6 mW/cm^2 (SAR range = 0 to 3.9 W/kg). Individual functions show air temperature selected and resulting colonic and mean skin temperatures during 10-min exposures to 450-MHz CW microwaves.

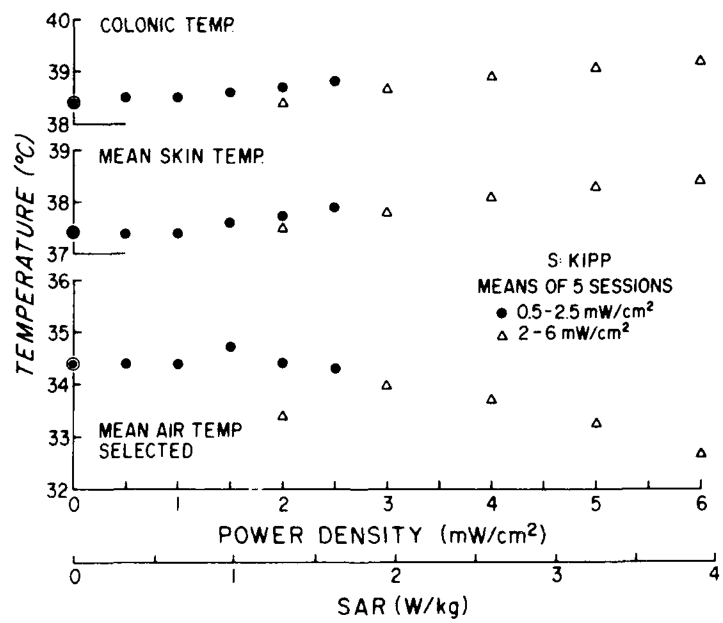


Figure 20. Summary of data from Experiments 1 and 2 (S:KIPP) covering power density range from 0 (control) to 6 mW/cm^2 (SAR range = 0 to 3.9 W/kg). Individual functions show air temperature selected and resulting colonic and mean skin temperatures during 10-min exposures to 450-MHz CW microwaves.

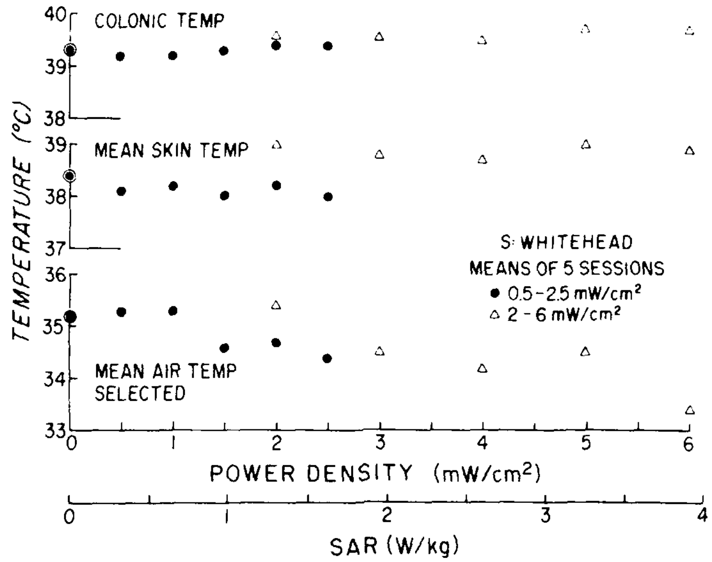


Figure 21. Summary of data from Experiments 1 and 2 (S:WHITEHEAD) covering power density range from 0 (control) to 6 mW/cm^2 (SAR range = 0 to 3.9 W/kg). Individual functions show air temperature selected and resulting colonic and mean skin temperatures during 10-min exposures to 450-MHz CW microwaves.

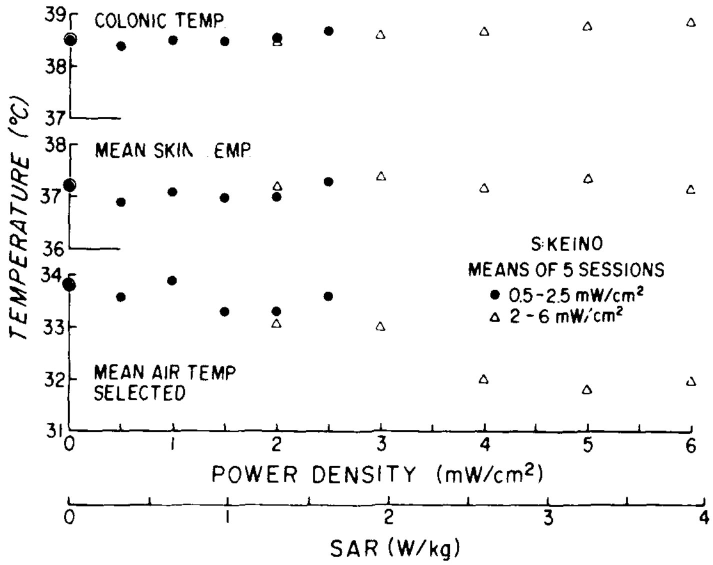


Figure 22. Summary of data from Experiments 1 and 2 (S:KEINO) covering power density range from 0 (control) to 6 mW/cm^2 (SAR range = 0 to 3.9 W/kg). Individual functions show air temperature selected and resulting colonic and mean skin temperatures during 10-min exposures to 450-MHz CW microwaves.

level of $\overline{T}_{sk}$ during the microwave exposure periods of Experiment 1 was about 1 °C higher than during those of Experiment 2. Combined data for the fourth monkey, S:Keino (Fig. 22), also show a gradual reduction of 1.8 °C in T_a selected across the range of power densities and only modest accompanying changes in $\overline{T}_{sk}$ and T_{co}.

Figure 24 presents grand means across all animals to summarize the results of Experiments 1 and 2. The construction and format of this figure is the same as the preceding four figures. Figure 23 demonstrates the continuous nature of the gradual reduction in T_a selected as the power density of the RF field increases. Standard errors of the individual means of T_a selected during microwave exposure range from 0.2 to 0.4 °C and the standard error of the baseline control mean is 0.15 °C. Although use of these control data is illegitimate in statistical tests to determine the threshold power density for the reduction of preferred T_a, the mean T_a selected at 3 mW/cm^2 lies 2 SEMs from the control level. This fact reinforces the provisional selection of 3 mW/cm^2 as the best estimate of the threshold power density for the alteration of thermoregulatory behavior by 450-MHz CW fields in the squirrel monkey.

The group mean data for T_{co} and $\overline{T}_{sk}$ shown in Figure 23 show little change across the range of power density explored in Experiments 1 and 2, rising only a few tenths of a degree C at the two highest power densities. It should be recalled, however, that individual animals often exhibited sharp increases in skin and deep body temperatures at the higher power densities during the sessions of Experiment 1.

Comparison with Results at 2450 MHz

Three of the four animal subjects in Experiments 1 and 2 had also been tested under an identical experimental protocol in our 2450-MHz exposure facility to determine the power density threshold for alteration of thermoregulatory behavior at this higher frequency. Five test sessions on two of the monkeys and four on the third had been conducted involving (following a 2-h stabilization period) five 10-min exposures to 2450-MHz CW microwaves at increasing power density (4, 6, 8, 10, and 12 mW/cm^2). This range of power

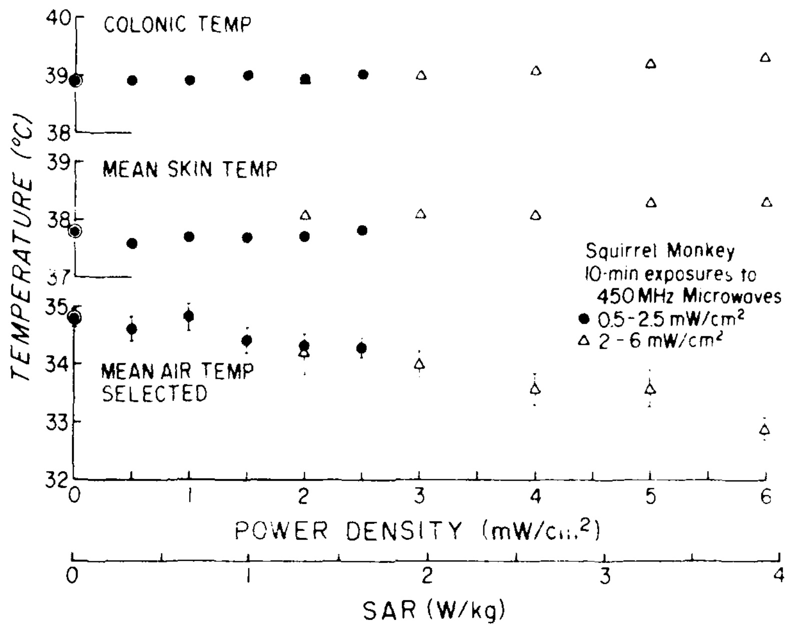


Figure 23. Mean air, skin, and colonic temperatures selected by 4 squirrel monkeys (5 sessions each) during 10-min exposures to 450-MHz CW microwaves at power densities from 0 (control) to 6 mW/cm^2 (SAR = 0 to 3.9 W/kg).

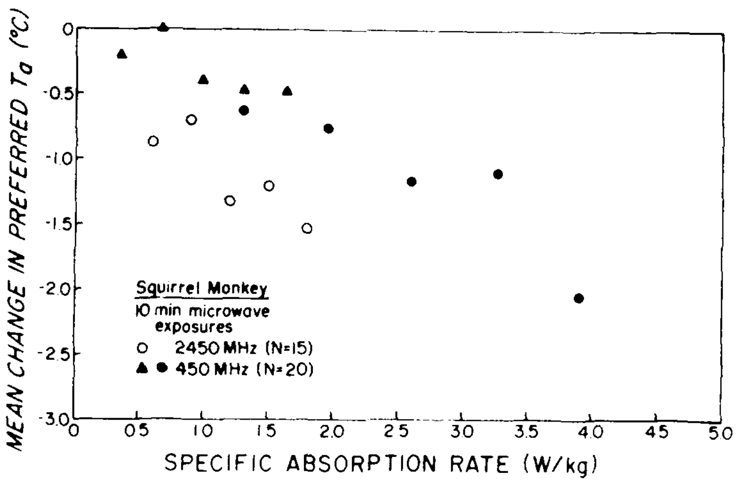


Figure 24. Mean change in air temperature preferred by squirrel monkeys during 10-min, low intensity exposures to both 450 MHz (solid circles) and 2450 MHz (open circles) as a function of specific absorption rate (SAR).

densities represented a range of SAR from 0.6 to 1.8 W/kg. The legitimacy of comparing results from the two exposure facilities is attested by the data in Figure 6 which shows, for one of the three monkeys, identical thermoregulatory behavior and associated body temperatures (microwaves absent) in the two test environments.

Figure 24 shows the mean change in preferred T_a (i.e., T_a selected) from the baseline level as a function of SAR at the two exposure frequencies, 2450 and 450 MHz. The points for the resonant frequency of 450 MHz are taken from Experiments 1 (solid circles) and 2 (solid triangles) described above, and are based on five experiments conducted on each of 4 monkeys. The points for the frequency of 2450 MHz are based on data collected from 3 of the 4 monkeys, as described above. (S:Whitehead did not participate in the experiments at 2450 MHz.) It is clear that at both frequencies, the higher the SAR, the greater the reduction in preferred T_a. However, at any given SAR, whole-body exposure to 2450 MHz microwaves stimulates a considerably greater reduction in preferred T_a than does exposure to 450 MHz. This difference is approximately 0.5 °C at the lower SARs and shows a tendency to increase as SAR increases. At the statistically-determined thresholds for the alteration of thermoregulatory behavior, SAR=1.2 W/kg at 2450-MHz (11) and 1.95 W/kg at 450 MHz (present report), the selected T_a is roughly 1.0 °C below that normally preferred when RF fields are absent at 2450 MHz and 0.8 °C at 450 MHz. By extrapolation, the SAR to reduce T_a by 1.0 °C in the presence of the resonant frequency is double the SAR at 2450 MHz to produce the same behavioral effect.

Discussion and Conclusions

All of the results of Experiments 1 and 2, together with comparison data collected on animals exposed to 2450 MHz fields, point to the inadequacy of behavioral thermoregulation in the presence of the resonant frequency. During brief (10-min) whole-body microwave exposures, the threshold for response change is higher and, as measured by changes in skin and deep body temperatures, thermoregulation is less efficient than at the higher frequency. To demonstrate these effects, we exposed the same experimental animals, under identical experimental protocols, to two exposure environments that were demonstrably equivalent, except for exposure frequency.

We have shown repeatedly (1,3,4,8,11,14,15) that thermoregulatory behavior exhibited by squirrel monkeys exposed to 2450-MHz CW microwave fields efficiently regulates the skin and deep body temperatures at the normally-preferred levels. This finding may be generalized to include partial body exposure (5), brief exposure to power densities as high as 70 mW/cm^2, and prolonged exposure to SARs as high as 6 W/kg (8). Brief exposure to the resonant frequency, on the other hand, often appears to produce inefficient behavior, as judged by the elevation in deep body temperature that occurs, even at SARs as low as 2 W/kg (Fig. 10). Sometimes this mild hyperthermia is accompanied by an elevated skin temperature (Fig. 10), but sometimes it is not (Fig. 12).

During exposure to conventional sources of convective or radiant heat, regulation of T_a such that skin temperature is at a level normally preferred will also yield a deep body temperature regulated at the characteristic normal level. We know that thermoregulatory behavior is usually triggered by stimulation of the thermosensitive neurons that reside near the surface of the skin. Therefore, we must conclude that during exposure to deeply-penetrating waves, such as occurs at the resonant frequency, these surface thermosensors are somehow inefficiently stimulated because far more of the energy is deposited in deep tissues. Unusual thermal gradients in the tissues will yield longer latencies to proximal stimulation of the sensory end organs, delayed signals to the sensory cortex, and abnormal behavior patterns. In the absence of efficient peripheral heat loss, the excessive heat generated deep in the body may quickly exceed the conductive capabilities of the circulatory system and lead to a bias or offset in the regulated variable, deep body temperature. This situation is identical to that which occurs during exercise, as has been demonstrated by Stitt (53) and elaborated by Shimada and Stitt (50).

Crucial to acceptance of this analysis is the demonstration that there is a significant delay in the mobilization of thermoregulatory behavior when a deeply-penetrating RF field first appears. The brief (10-min) exposure periods of Experiments 1 and 2 are inadequate to quantify response latency; much longer exposure periods, leading to steady-state behavioral responding, are necessary. Therefore, we conducted Experiment 3 to probe the evolution of thermoregulatory behavior and regulated body temperatures across a prolonged (90-min) period of exposure to the resonant frequency. We had previously conducted experiments in which squirrel monkeys underwent prolonged whole-body exposure to 2450 MHz CW microwaves at power densities that ranged from 10 to 45 mW/cm^2 (8,14). Experiment 3 was designed similarly to these earlier studies so that direct comparison of effects at the two frequencies could be made.

EXPERIMENT 3: BEHAVIORAL THERMOREGULATION DURING PROLONGED MICROWAVE EXPOSURE AT THE RESONANT FREQUENCY

Introduction

It is well recognized, and has been emphasized throughout this report, that sensory appreciation of tissue heating during RF exposure is necessary for the initiation of appropriate behavioral action. Whether a microwave exposure produces a thermal sensation depends upon many parameters of the RF signal, notably frequency, polarization, modulation, intensity, duration, and the surface area of the body exposed. Michaelson (44) provided a comprehensive review of the early studies concerned with the perception of microwaves.

Historically, exposure duration has received appreciably less experimental attention than some of the other parameters cited, except for loose designations such as "acute" (brief, short term, measured in minutes) or "chronic" (long term, measured in days, weeks, etc.). In our own experimental work to quantify thermoregulatory responses in experimental animals exposed to RF fields, we have contrasted "brief" exposures (5 to 10 min) with "prolonged" exposures (90 to 240 min) that are sufficient to produce a thermoregulatory steady-state. An early study from our laboratory (14) investigated the role of exposure duration in the development of efficient thermoregulatory behavior in the presence of 2450 MHz CW microwaves. Suprathreshold power densities (10 and 20 mW/cm^2), at durations from 5 to 150 min, were presented to squirrel monkeys engaged in thermoregulatory behavior of the type studied in Experiments 1 and 2. The results showed that all durations longer than 5 min stimulated a significant reduction in selected T_a. Further, a duration of about 25-30 min was necessary to achieve a stabilization of preferred T_a, after which no further significant adaptation occurred (to a maximal exposure duration of 150 min).

Experiment 3 was designed to investigate the time course of the behavioral thermoregulatory response during "prolonged" whole-body exposure of the squirrel monkey to the resonant frequency, 450 MHz. Critical questions to which we sought answers were related to the latency of response initiation, the time required to achieve stabilization of thermoregulatory behavior, and the potential for adaptation of the behavioral response as exposure duration increased. So that we might compare the results with those of Experiments 1 and 2, and also take advantage of control data (microwaves absent) already in hand, the same 4 monkeys served as subjects in Experiment 3 as had served in the earlier experiments.

Methods and Procedure

As noted above, the same four squirrel monkeys served as subjects in Experiment 3. The range of average body mass was now 825 to 1140 g. Housing and feeding regimes had not changed.

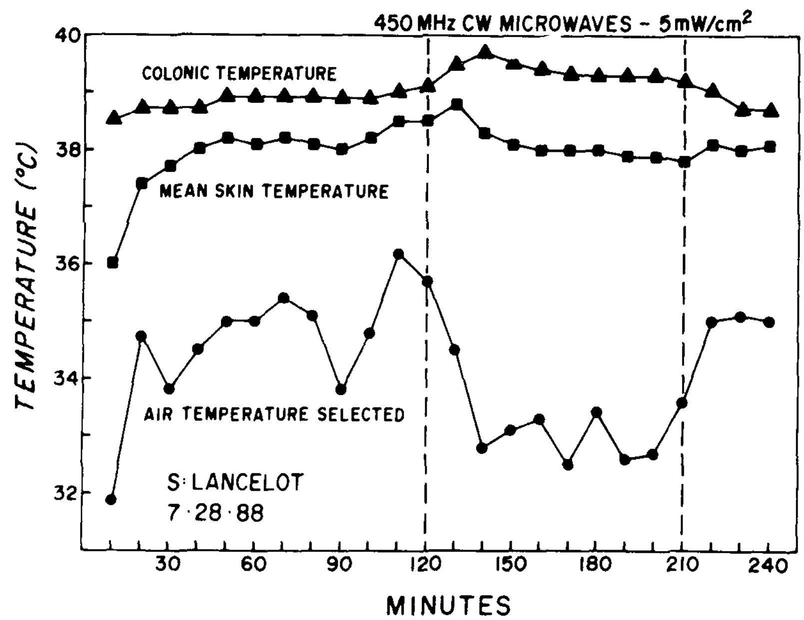


Figure 25. Representative experiment on one monkey (S:LANCELOT) to illustrate behavioral thermoregulation during one 90-min exposure to 450-MHz CW microwaves at 5 mW/cm^2 (SAR = 3 W/kg). Individual functions show mean air temperature selected (circles) and resulting colonic (triangles) and mean skin (squares) temperatures.

The apparatus, response measures, and behavioral contingencies were identical to those described for Experiment 1. A single power density, 5 mW/cm^2 (SAR=3.2 W/kg) was selected for study, which was above threshold for all animals, and was well tolerated by all when presented for the 10-min duration of Experiment 1. An initial 2-h period for stabilization of thermoregulatory behavior was followed by a single 90-min exposure to 450-MHz CW microwaves at the 5 mW/cm^2 power density. A 30-min period of behavioral thermoregulation (RF absent) terminated the session. Five such experiments were conducted on each of the four monkeys. In addition, five experiments each were conducted on all of the monkeys in the 2450-MHz exposure facility using an identical protocol and a power density of 20 mW/cm^2 (SAR=3 W/kg). To serve as comparison data, five 4-h sessions of behavioral thermoregulation (RF absent) were conducted on each of the four animals in the 450-MHz exposure facility.

Results

The data from Experiment 3 were analyzed in identical fashion to those of Experiments 1 and 2. Means values (±1 SEM) of each measured dependent variable were computed for each 10-min segment of each session across the five experimental sessions for a given animal. Identical data analysis was used for the experiments conducted in the 2450-MHz exposure facility and the control (RF absent) experiments. In all cases, the T_a selected by the animal was determined from the temperature recorded at the air outlet, digitized at 1-min intervals.

Figure 25 shows a representative experiment on one monkey (S:Lancelot) to illustrate the general characteristics of the responses observed during 90-min whole-body exposures to the resonant frequency. During the first 10 min after the RF field was turned on, the animal began to select a cooler T_a; both $\overline{T}_{sk}$ and T_{co} increased significantly during this time. An additional 10 min was required in this test session before the monkey had lowered the T_a to a level that was sustained for the remainder of the exposure period. During this second 10-min period, $\overline{T}_{sk}$ began to fall back toward the level regulated during the baseline stabilization period. However, T_{co} continued to rise and, close

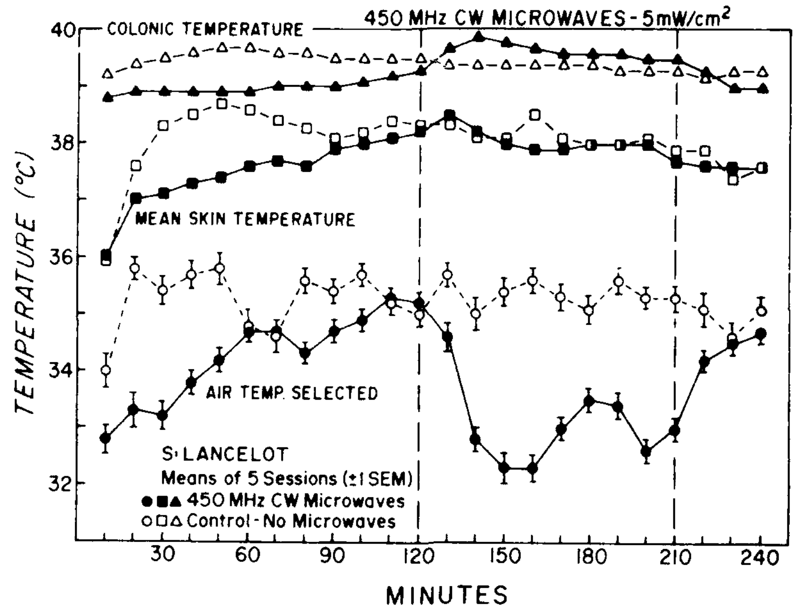


Figure 26. Five-experiment mean of air temperature selected (solid circles) by one monkey (S:LANCELOT) during whole-body exposure to 450-MHz CW microwaves for 90 min at a power density of 5 mW/cm^2 compared with five control experiments (open circles) in which no microwaves were present. Also shown are the resulting colonic (triangles) and mean skin (squares) temperatures. Error bars represent ± 1 SEM.

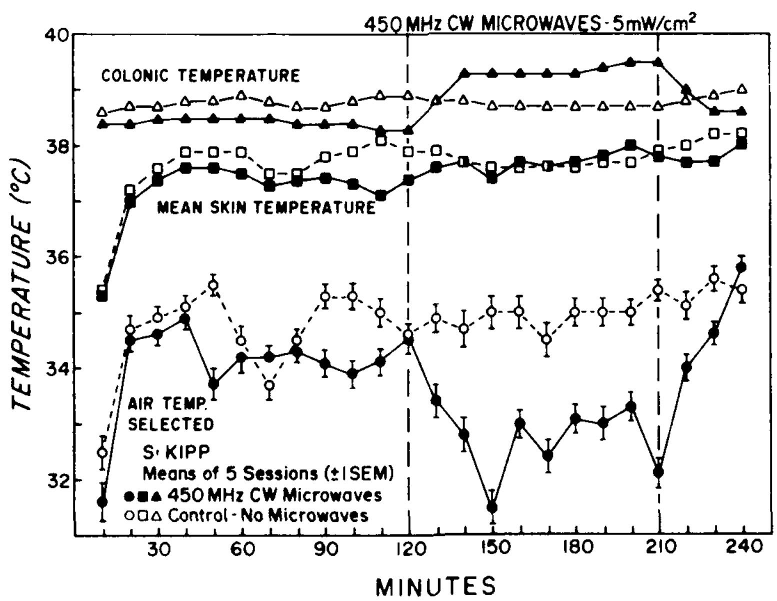


Figure 27. Five-experiment mean of air temperature selected (solid circles) by one monkey (S:KIPP) during whole-body exposure to 450-MHz CW microwaves for 90 min at a power density of 5 mW/cm^2 compared with five control experiments (open circles) in which no microwaves were present. Also shown are the resulting colonic (triangles) and mean skin (squares) temperatures. Error bars represent ± 1 SEM.

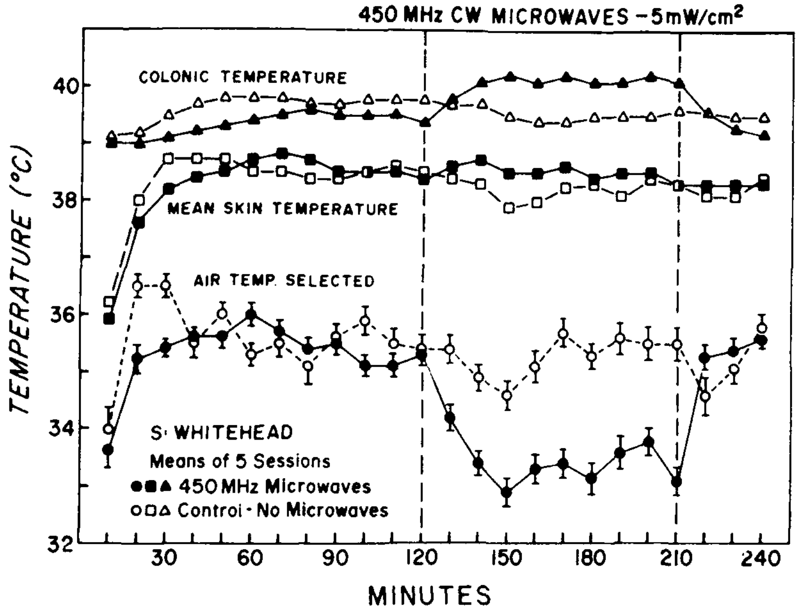


Figure 28. Five-experiment mean of air temperature selected (solid circles) by one monkey (S:WHITEHEAD) during whole-body exposure to 450-MHz CW microwaves for 90 min at a power density of 5 mW/cm^2 compared with five control experiments (open circles) in which no microwaves were present. Also shown are the resulting colonic (triangles) and mean skin (squares) temperatures. Error bars represent ± 1 SEM.

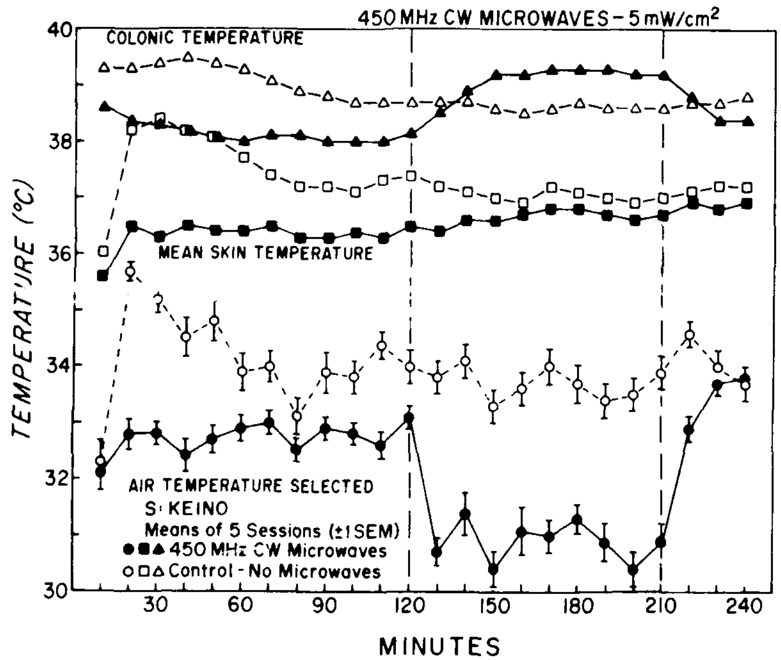


Figure 29. Five-experiment mean of air temperature selected (solid circles) by one monkey (S:KEINO) during whole-body exposure to 450-MHz CW microwaves for 90 min at a power density of 5 mW/cm^2 compared with five control experiments (open circles) in which no microwaves were present. Also shown are the resulting colonic (triangles) and mean skin (squares) temperatures. Error bars represent ± 1 SEM.

to the end of the first hour of exposure, a stable elevated level was attained. Extinction of the field at the end of the 90-min exposure period provoked restoration of the T_{co}, $\overline{T}_{sk}$, and T_a normally preferred when the RF field was absent.

Group Data at 450 MHz

Figures 26 through 29 show, for each of the test animals, the mean T_a selected (solid circles), together with the resulting mean T_{co} (solid triangles) and $\overline{T}_{sk}$ (solid squares), measured in five experiments in which the animals were exposed for a single 90-min period to 450-MHz CW microwaves at a power density of 5 mW/cm^2. Comparable data collected during the five control experiments, when microwaves were absent, are shown in open symbols. As before, each plotted symbol represents the mean value calculated over the preceding 10-min period. The error bars on the T_a selected data represent ± 1 SEM; in general, the SEMs for means of $\overline{T}_{sk}$ and T_{co} were smaller than the symbols used to plot the data.

The mean data in Figures 26 through 29 show clearly that, at microwave onset, all animals required at least 30 min to attain the stabilized level of T_a that would characterize the remainder of the 90-min exposure period. During the initial 20-30 min of RF exposure, T_{co} rose to a stabilized level up to 1.0 °C above that of the initial baseline period or the regulated level during the control experiments (open symbols). In most cases, the steady-state $\overline{T}_{sk}$ produced by behavioral alterations of T_a was little different from that normally preferred when the RF field was absent. Analysis of the data for S:Keino (Fig. 29) is not quite so clearcut because of the shift in baseline that occurred between the contol series (open symbols) and the sessions of Experiment 3 (solid symbols) that were collected more than one year later. Nevertheless, there is no question regarding the substantial offset in T_{co} that occurred during the 90-min exposure to 450-MHz waves.

The data for all animals were used to calculate grand means of each dependent variable and are presented in Figure 30 to illustrate these specific trends in the data as clearly as possible. The error bars for $\overline{T}_{sk}$ and T_a

selected represent ± 1 SEM; error bars are not shown for T_{co} because they are smaller than the symbols used to plot the data. The group data demonstrate dramatically that during a 90-min exposure to the resonant frequency, squirrel monkeys select a T_a about 2 °C cooler than they prefer when the field is absent, and thereby regulate $\overline{T}_{sk}$ at the level normally preferred. Thirty to forty minutes are required for this behavior to stabilize. The pattern of behavioral thermoregulation is such that an increment of nearly 1 °C is generated in T_{co}; this offset is sustained for the duration of the RF exposure.

<u>Comparison with Results at 2450 MHz</u>

The four animal subjects in Experiment 3 had also been tested under an identical experimental protocol in our 2450-MHz exposure facility to determine the time course of behavioral thermoregulation and associated body temperatures at this higher frequency. The power density during the single 90-min RF exposure was 20 mW/cm^2; on the basis of several types of dosimetric studies (8), the SAR at 2450 MHz was determined to be 0.15 $(W/kg)/(mW/cm^2)$. Thus, for comparison, the SAR at 2450 MHz was similar to that at 450 MHz, approximately 3 W/kg. Five test sessions on each of the four monkeys were conducted in the 2450-MHz exposure facility. Once again, the legitimacy of comparing data from the two exposure facilities is reinforced by the data in Fig. 6 which shows, for one of the monkeys, identical thermoregulatory behavior and associated body temperatures (microwaves absent) in the two test environments.

Figure 31 shows the mean T_a selected (± 1 SEM) by one of the monkeys (S:Lancelot) during five test sessions in each test environment; T_a selected during 2450-MHz exposure is plotted in solid circles, while T_a selected during 450-MHz exposure is plotted in open circles. The associated $\overline{T}_{sk}$ (solid and open squares) and T_{co} (solid and open triangles) produced by the behavior are also shown. Considering that nearly two years elapsed between the experimental series at the two frequencies, it is not surprising that the data collected in the baseline stabilization periods are so dissimilar in character. However, the responses measured in the final 30 min of the

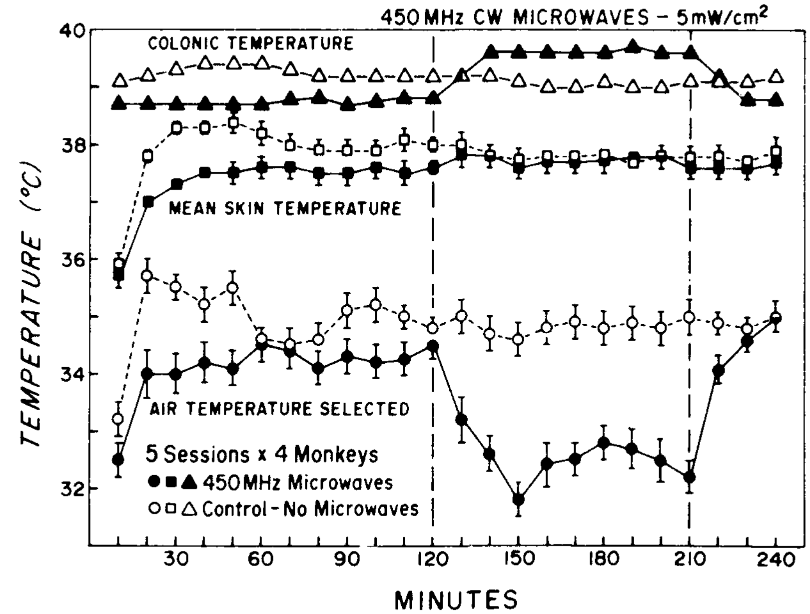


Figure 30. Mean air temperature selected (solid circles) by four squirrel monkeys (five sessions each) during whole-body exposure to 450-MHz CW microwaves for 90 min at a power density of 5 mW/cm^2 (SAR = 3 W/kg) compared with five control experiments conducted on each monkey (open circles) when no microwaves were present. Also shown are the resulting colonic (triangles) and mean skin (squares) temperatures. Error bars represent ± 1 SEM.

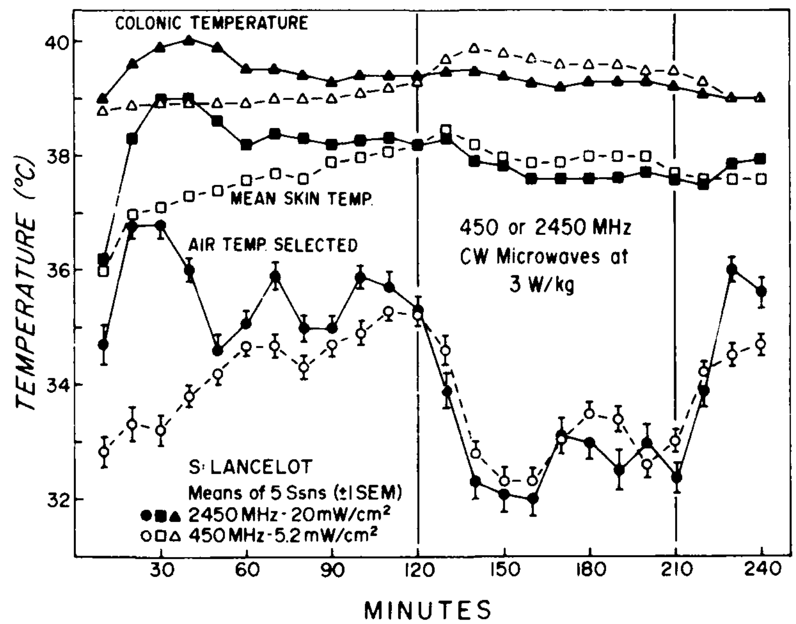


Figure 31. Mean air temperature selected (circles) in five sessions by one monkey (S:LANCELOT) during one 90-min exposure of the whole body to 450-MHz (open symbols) or 2450-MHz (solid symbols) CW microwaves. Also shown are the resulting colonic (triangles) and mean skin (squares) temperatures. Error bars represent ± 1 SEM.

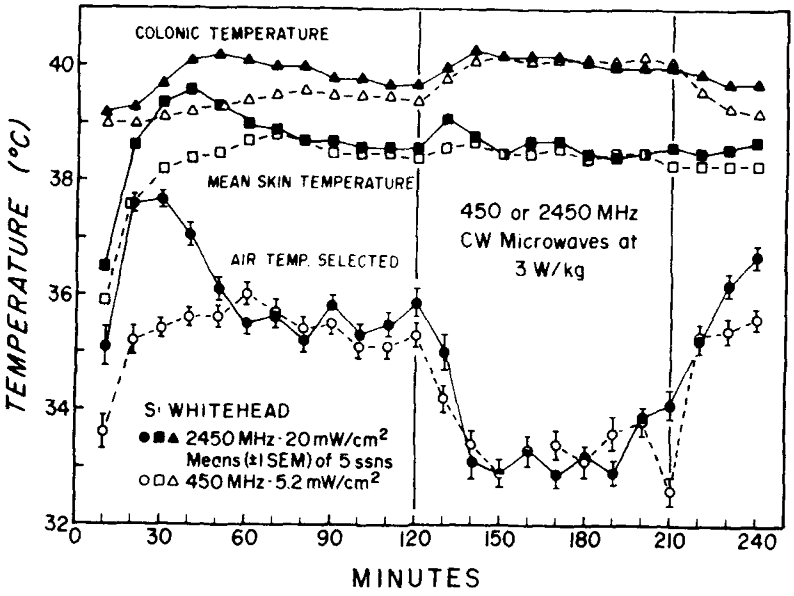


Figure 32. Mean air temperature selected (circles) in five sessions by one monkey (S:WHITEHEAD) during one 90-min exposure of the whole body to 450-MHz (open symbols) or 2450-MHz (solid symbols) CW microwaves. Also shown are the resulting colonic (triangles) and mean skin (squares) temperatures. Error bars represent ± 1 SEM.

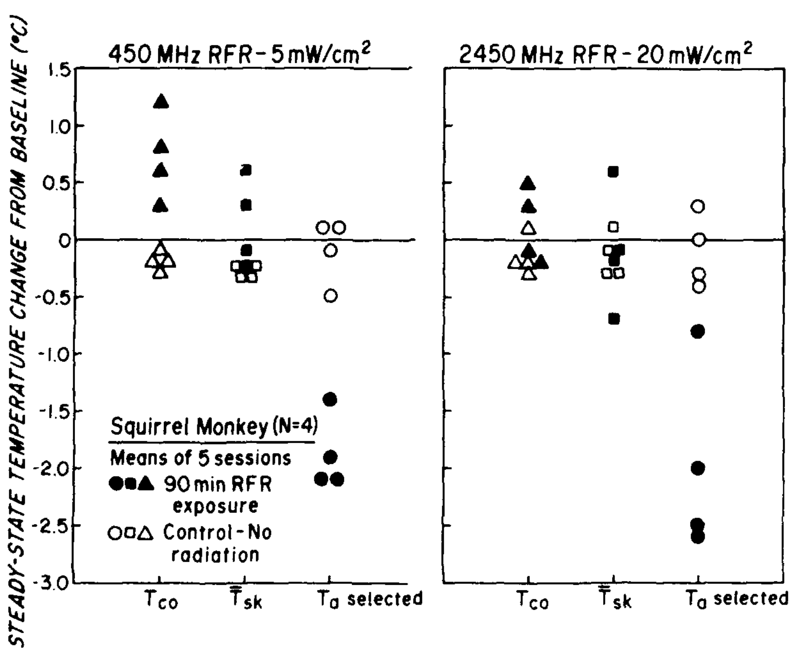


Figure 33. Analysis of group data (N=4) for behavioral thermoregulation during single 90-min exposures of the whole body to 450-MHz (left panel) and 2450-MHz (right panel) CW microwaves when SAR = 3 W/kg at each frequency. Solid symbols represent data collected during RF exposure; open symbols represent data collected during control experiments when no RF was present. Mean steady-state change from baseline level in air temperature selected (circles) is shown together with the change in colonic (triangles) and mean skin (squares) temperatures. See text for details.

baseline period are similar enough to allow comparison of the data collected during the 90-min exposure period at 2450 and 450 MHz. The figure shows that th. time course of behavioral thermoregulation, when an RF field at 3 W/kg is presented, is not substantially different at the two frequencies. In detail, the latency to attain the final preferred T_a may be a few minutes longer and the steady-state T_a selected may be higher by a few tenths of a degree at 450 MHz; however, these differences are probably not reliable. Further, the regulated level of $\overline{T}_{sk}$ in the steady state, while slightly elevated at 450 MHz, is not reliably different from the $\overline{T}_{sk}$ at 2450 MHz. However, the regulated increase in T_{co} when the resonant frequency is imposed is nearly 0.5 °C in the steady state, whereas during 2450-MHz exposure, the steady-state T_{co} does not differ from the baseline level.

Comparable data collected at the two frequencies on a second monkey (S:Whitehead) are shown in Figure 32. The shift in baseline responses for this monkey was not excessive, except for the regulated level of T_{co} which averaged 0.3 °C lower at the time of the 450-MHz series than at the time of the 2450-MHz series. There is no reliable difference in the time course of the change in T_a selected, when the RF field was present, or in the regulated level of $\overline{T}_{sk}$ at the two frequencies. The regulated elevation in T_{co} was 0.8 °C at 450 MHz and 0.5 °C at 2450 MHz, a difference of 0.3 °C.

Figure 33 summarizes the data collected on the four test animals for both RF frequencies in terms of the steady-state change in temperature from the baseline level. To construct this figure, means were calculated for each dependent variable across the final 30 min of the baseline stabilization period and the final 30 min of the 90-min exposure period; the difference between these means is plotted for individual monkeys for responses to whole-body exposure to 450 MHz (left panel) and to 2450 MHz (right panel). Use of the stabilized baseline data from each experiment as control (comparison) data eliminates any discrepancies that may be related to baseline shifts over time, such as those described above.

Inspection of Figure 33 reveals several aspects of the responses of the four monkeys that are directly related to the patterns of energy absorption at the two frequencies employed. At the outset, it is important to remember that the SARs at the two frequencies studied (3 W/kg) were approximately the same. Irradiation at either frequency produced selection of a cooler environment (averaging 1.8 °C below baseline at 450 MHz, 1.9 °C below baseline at 2450 MHz) such that the skin temperature, on average, was regulated at the level normally preferred (0.2 °C above baseline at 450 MHz, 0.06 °C below baseline at 2450 MHz). However, the regulated level of T_{co} produced by the behavioral change was about 0.5 °C higher at the resonant frequency than at 2450 MHz (0.74 °C above baseline at 450 MHz, 0.27 °C above baseline at 2450 MHz). Thus, while $\overline{T}_{sk}$ was regulated efficiently by behavioral alteration of T_a at both frequencies, T_{co} was substantially elevated above the normal level during exposure to the resonant frequency.

Discussion and Conclusions

These experiments have investigated changes in behavioral thermoregulation, and associated changes in body temperatures, when experimental animals are subjected to whole-body exposure at resonant and supraresonant microwave frequencies. We have shown that prolonged exposure of the squirrel monkey to the resonant frequency (450 MHz), such that thermoregulatory responses attain the steady-state, reveal few differences that can be attributed directly to frequency except for a higher level of regulated body temperature than is associated with exposure at 2450 MHz. There are subtle indications of a slightly longer latency to achieve a preferred T_a and a slightly warmer preferred T_a when the resonant frequency is present, but neither of these trends are statistically reliable. In any case, prolonged exposure allows for the amelioration of temperature offsets over time that may occur quickly upon the initiation of exposure to the resonant frequency. Usually within 30 min, behavioral responses have generated the preferred T_a to achieve a thermoregulatory steady-state, and further exposure yields few additional modifications in T_a selected or the body temperatures achieved thereby.

The greater increase in T_{co} at resonance is obviously due to the deeper penetration of the longer waves into body tissues. The picture presented by an animal engaged in active behavioral thermoregulation, when exposed for an extended period to the resonant frequency, is identical to that which occurs during exercise (Stitt, 1979). One can think of the heat generated passively in deep tissues as comparable to heat generated in the working muscles during exercise. At the initiation of exercise, metabolic heat production increases to a high level in a stepwise fashion. At the same time, the mobilization of mechanisms to transfer that heat to the body surface for loss to the environment is sluggish, as are the peripheral mechanisms of heat loss, and thus body heat loss will lag well behind heat production. The net result will be an increase of heat stored in the body, and a resultant increase in the deep body temperature. In the steady-state, as heat loss responses are mobilized, total body heat loss will equal heat production, and body temperature will stabilize at a level that depends on the level of exercise being performed. Nielsen and Nielsen demonstrated these basic comparisons several years ago for human subjects, passively heated by diathermy vs exercising on a bicycle ergometer (48). Our data on the squirrel monkey, behaviorally thermoregulating in the presence of 450-MHz microwaves, corroborate these earlier findings.

The fact that a cooler-than-normally-preferred $\bar{T}_{sk}$ was not selected immediately by the squirrel monkeys in our experiments to prevent a buildup of heat in the body core is partly related to built-in latencies in the physiological systems of the body. It is also possibly related to inefficient stimulation of the surface thermoreceptors by the deeply-penetrating radiation. At a supraresonant frequency of 2450 MHz and SARs as high as 9 W/kg, squirrel monkeys will rapidly reduce T_a behaviorally during a 10-min RF exposure so that T_{co} is regulated efficiently at the normal level (8,9). This response is as much due to efficient stimulation of thermosensors in the skin that drive behavioral responses as it is to the fact that the radiation does not penetrate much more than 1-2 cm below the skin surface.

We have demonstrated that during prolonged exposure at the resonant frequency, behavioral responses adjust T_a such that $\bar{T}_{sk}$ is regulated with considerable precision at the level normally preferred. If thermosensors in the skin are inefficiently stimulated by deeply-absorbed radiation and thermal gradients in the tissues are abnormal, it is pertinent to ask how the behavioral responses are energized and such precise regulation of $\bar{T}_{sk}$ is accomplished. One answer may lie in the mobilization of autonomic thermoregulatory responses that are manifested peripherally. For example, an increase in either skin or deep body temperature can control the initiation of thermoregulatory sweating (45,46) which, in turn, can provide stimulation of skin receptors as the fluid evaporates from the skin surface. Also, stimulation of deep body as well as skin thermoreceptors can initiate peripheral vasodilation which, in turn, will be sensed as changes in skin temperature (12,54). We hypothesized that peripherally-manifested autonomic thermoregulatory responses, generated by exposure to RF fields at the resonant frequency, could indirectly aid the sensation of these fields and, thus, contribute to the control of behavioral thermoregulatory responses. We designed Experiment 4 as a first step in testing this hypothesis.

EXPERIMENT 4: AUTONOMIC CORRELATES OF CHANGES IN THERMOREGULATORY BEHAVIOR

Introduction

As stated above, our working hypothesis for Experiment 4 was that the peripheral manifestation of autonomic thermoregulatory responses could reinforce the sensation of an imposed deeply penetrating RF field. Sensation provided indirectly in this manner could augment the direct (although inefficient at resonance) stimulation of the peripheral thermosensors that normally mobilize thermoregulatory behavior. Although it is very difficult to prove this hypothesis directly, we hoped to provide convincing indirect evidence. This evidence would take the form of associations between thresholds for mobilization of specific autonomic heat loss responses and thresholds already determined for the alteration of thermoregulatory behavior.

Our strategy in designing the experiment was based upon consideration of the thermoregulatory profile for the squirrel monkey (Fig. 1). When given the opportunity to thermoregulate behaviorally, squirrel monkeys choose thermal environments (T_a) for themselves that lie at the upper end of the TNZ, i.e., near 35 °C (5). At this temperature, the animal should be fully vasodilated but not sweating. Any external source of energy imposed on the animal in this environment will either provoke a reduction in selected T_a or initiate thermoregulatory sweating. When the air surrounding the animal is moving rather than stationary, convective heat loss will tend to modify the effective temperature of the environment for comfort (19,22,23). Thus, in a moving airstream such as that which prevails in the test compartment for squirrel monkeys (Fig. 5), the effective or operative temperature selected by the animal will be a few degrees lower than the dry bulb temperature measured in the air outlet, and will place the animal slightly below the UCT in the thermoregulatory profile of Figure 1.

A wealth of experimental evidence supports the conclusion that exposure of experimental animals to microwave fields will alter autonomic thermoregulatory responses (7). Thresholds for mobilization of specific autonomic responses, in terms of power density or SAR, can be determined at a wide range of T_a below that at which the response naturally occurs (8; also see the Introduction to this report). In Experiment 4, the stage was set to initiate peripheral vasodilation and/or sweating by brief RF exposures conducted in a constant environment similar to that chosen by the animals themselves. We hoped thereby to demonstrate a similarity in thresholds for both behavioral thermoregulatory changes (measured earlier in Experiments 1 and 2) and autonomic response changes. Although correlation does not provide causation, positive results would strengthen the hypothesis that skin temperature changes associated with the mobilized autonomic responses could contribute to the cueing of thermoregulatory behavior.

Methods and Procedure

Four adult male squirrel monkeys served as subjects in Experiment 4. One had been a subject in Experiments 1, 2, and 3, while all others had been extensively exposed to 2450-MHz fields, but were naive to 450-MHz exposure. One of these three was implanted with a pair of Teflon re-entrant tubes in the medial preoptic area of the hypothalamus (15); the probe of a Vitek Electrothermia Monitor could be inserted into one of these tubes during the experiments to monitor changes in hypothalamic temperature (T_{po}). Housing and maintenance procedures were the same as for Experiments 1-3. The range of average body masses for the four animals was roughly 850 - 1300 g during the course of the experiment.

During the experimental sessions, individual animals were chair restrained in the far field of the dipole antenna inside the 450-MHz exposure chamber. The chair was enclosed by a Styrofoam compartment as shown in Figure 5, but in this case the animal had no control over the temperature of the air that flowed through the test compartment. Air at a constant temperature of 34 °C (± 0.5 °C) circulated at 0.36 m/s through the compartment in the direction shown by the arrows. The T_a was sensed by a copper-constantan thermocouple in the air outlet from the anechoic chamber and recorded every minute by an online computer. The monkey was under constant video surveillance.

Colonic and four skin temperatures were monitored at 1-min intervals in the same manner as in the previous experiments. In the one implanted animal, T_{po} was measured, as well as T_{co}. Oxygen consumption ($\dot{V}O_2$) was measured using an open-flow draw system. Chamber air was drawn at a constant rate of 7 L/min through a Plexiglas hood over the monkey's head and thence outside the chamber through Tygon tubing. The oxygen partial pressure (PO_2) deficit was measured downstream by a Beckman Model 755 paramagnetic oxygen analyzer that sampled the passing airstream at a rate of 0.3 L/min. Metabolic heat production ($\underline{M}$) was calculated from $\dot{V}O_2$ assuming a constant RQ of 0.83 (35,51).

Thermoregulatory sweating from the right foot was measured with a T_{dp} sensing device developed at the *Pierce Foundation Laboratory* (32). The monkey wore an L-shaped Plexiglas boot with the sole of the foot resting on a nylon support. Chamber air was drawn through the boot, at the rate of 1.9 L/min, and thence outside the chamber through Tygon tubing where T_{dp} was measured and recorded continuously. Sweating rate ($\dot{m}_{sw}$) was calculated from T_{dp} using Antoine's equation and a modified gas equation (8,57).

Each experimental test session on a single monkey involved equilibration of the animal for 120 min to the prevailing T_a (34 °C) followed by a series of 4 brief exposures to 450-MHz CW microwaves at increasing power density. The first 3 exposures were of 10-min duration at power densities of 2, 4, and 6 mW/cm^2. The fourth exposure was of 20-min duration at a power density of 8 mW/cm^2. Each exposure was followed by a 20-min restabilization period (RF absent) and the session ended with a 20-min period of re-equilibration. All test sessions were conducted in the morning to avoid possible circadian shifts in resting levels of thermoregulatory processes. At specific times during the test, 5-min baseline checks of the O_2 content of the chamber air were made to track any possible drifts in baseline levels. A second T_{dp} sensor monitored

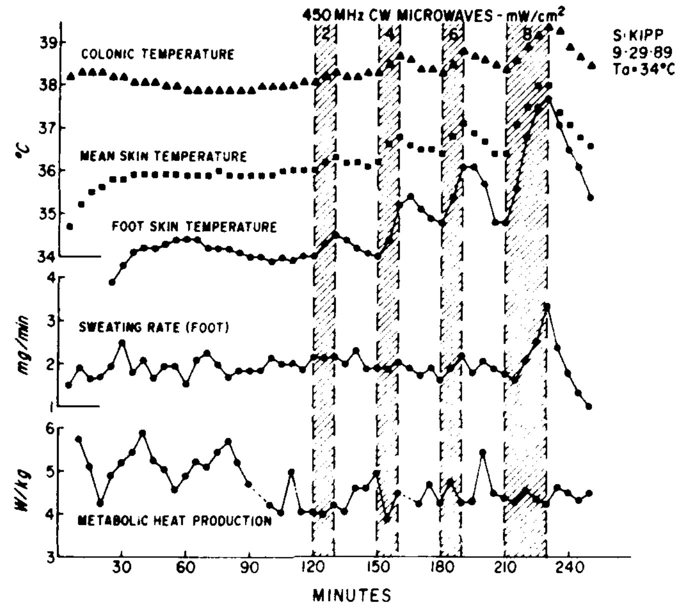


Figure 34. Representative experiment on one monkey (S:KIPP) to determine changes in body temperatures (colonic, mean skin, foot skin), sweating rate, and metabolic heat production during brief exposures of the whole body to 450-MHz CW microwaves at an ambient temperature (T_a) of 34 °C.

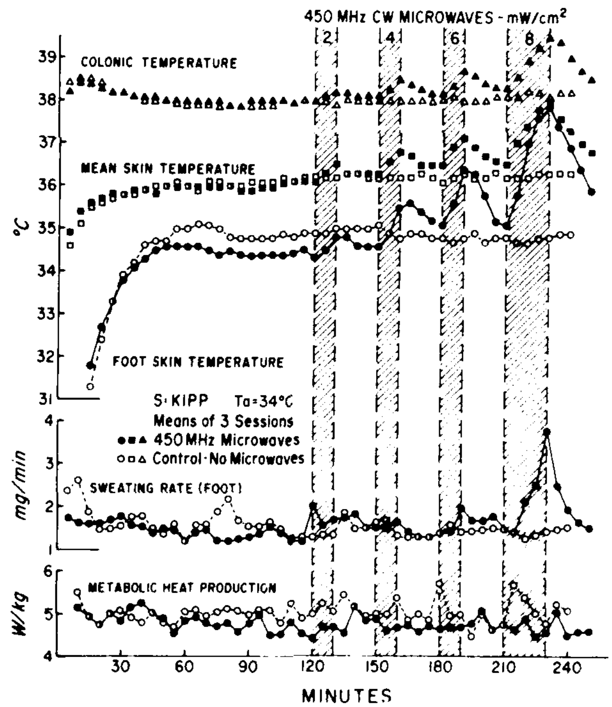


Figure 35. Mean changes (3 experimental sessions) in colonic temperature, mean skin temperature and foot skin temperature, sweating rate, and metabolic heat production of one monkey (S:KIPP) during brief exposures of the whole body to 450-MHz CW microwaves (solid symbols) compared with control experiments (open symbols) when no microwaves were present. Ambient temperature (T_a) was constant at 34 °C. Individual points represent means of the preceding 5 minutes.

chamber source air continuously. Throughout the test session, all data were sampled at 1-min intervals by an online computer. At the end of the session, after the animal had been removed from the test compartment and returned to the home cage, a 10- to 20-min baseline check of the physical characteristics of the chamber air completed the test data.

Three experimental test sessions, as described above, were conducted on each of the four monkeys. To serve as comparison data, three baseline sessions at T_a=34 °C with microwaves absent were conducted on each animal.

Results

The data from individual test sessions were analyzed in 5-min time bins (i.e., means and standard errors of each dependent variable were calculated at 5-min intervals across the duration of the test session). A sample experiment on one monkey (S:Kipp) appears in Figure 34 to illustrate both the protocol and representative results obtained. During the 120-min baseline equilibration period, all measured dependent variables stabilized at values predictable from the thermoregulatory profile and correlated steady-state body temperatures of the squirrel monkey (Figs. 1, 2). Figure 34 shows that the colonic temperature was regulated at the normal level, the measured foot skin temperature (T_{ft}) indicated that the foot was partially vasodilated, metabolic heat production was steady at a low, resting level, and the animal was not sweating. Passive heating of the foot accompanied brief exposure to the resonant frequency at 2 mW/cm^2. The next RF exposure (4 mW/cm^2) initiated active vasodilation of the foot, exemplified by the discontinuity in the slope of the T_{ft} curve; no sweating occurred. Exposure at 6 mW/cm^2 further increased vasodilation of the foot, while exposure at 8 mW/cm^2 initiated sweating from the foot in addition to a completion of foot vasodilation. A passive increase of 1.1 °C in T_{co} also occurred during the 20-min exposure at 8 mW/cm^2, despite full peripheral vasodilation and the initiation of vigorous sweating. An absence of changes in $\underline{M}$ indicated that the sweating was truly thermoregulatory and not emotional (6). It is of interest that, in this experiment, vasodilation of the foot was well underway (at T_a=34 °C) at a power density (4 mW/cm^2) close to the threshold for alteration of thermoregulatory behavior in this animal (2 mW/cm^2).

Mean Data for all Subjects

The mean data for S:Kipo, calculated across three experimental sessions, are shown in Figure 35 (solid symbols), and compared with mean control data when microwaves were absent (open symbols). The conclusions derived from the individual experiment displayed in Figure 34 are reinforced by the mean data of Figure 35, collected in 3 experimental sessions. Active vasodilation of the foot occurred at 4 mW/cm^2, as evidenced by a sharp increase in the temperature of the foot skin. This response was augmented at higher power densities and supplemented by vigorous foot sweating at 8 mW/cm^2. Comparable mean data, calculated across 3 experimental sessions, are shown in Figures 36 and 37 for two other monkeys. Both monkeys exhibited substantial vasodilation of the foot (i.e., sharply increased T_{ft}) at power densities of 4 mW/cm^2 and above. This autonomic response was augmented by foot sweating at the higher power densities of 6 and 8 mW/cm^2, in the absence of significant changes in $\underline{M}$. Thus, the sweating was truly thermoregulatory.

Specific Effects on Hypothalamic Temperature

A slightly different pattern of responses was exhibited by the one monkey (S:Paul) with Teflon reentrant tubes implanted in the brainstem so that brain temperature (T_{po}) could be measured during the experiments. At the stabilized T_a of 34 °C, this monkey was almost fully vasodilated such that only slight increments in T_{ft} could be measured during the brief exposures to 450-MHz fields. The results of a single experiment (Fig. 38) show that the principal response to imposition of the RF field was initiation of thermoregulatory sweating from the foot. An increase in sweating rate during the 10-min exposure at 2 mW/cm^2 was augmented during the subsequent exposures at 4 and 6 mW/cm^2. Profuse sweating occurred during the 20-min RF exposure at 8 mW/cm^2, in the absence of any changes in $\underline{M}$. It is notable that the brain temperature, riding the normal 0.3 °C above T_{co}, sustained no substantially different temperature elevations during RF exposure than did T_{co}. Thus, at the resonant

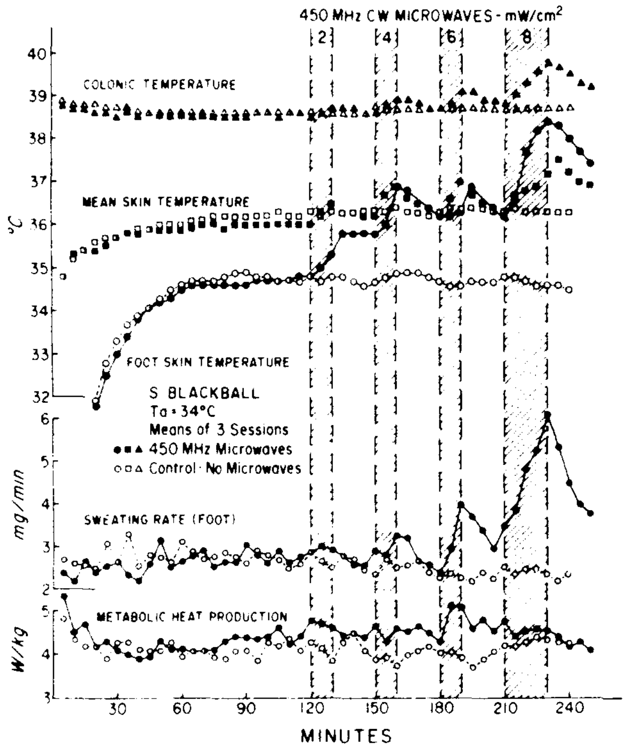


Figure 36. Mean changes (3 experimental sessions) in colonic temperature, mean skin temperature and foot skin temperature, sweating rate, and metabolic heat production of one monkey (S:BLACKBALL) during brief exposures of the whole body to 450-MHz CW microwaves (solid symbols) compared with control experiments (open symbols) when no microwaves were present. Ambient temperature (T_a) was constant at 34 °C. Individual points represent means of the preceding 5 minutes.

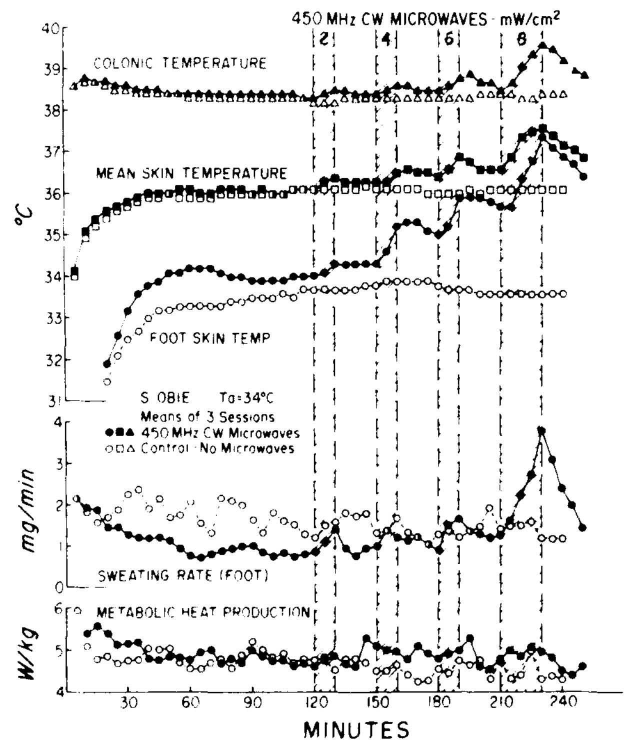


Figure 37. Mean changes (3 experimental sessions) in colonic temperature, mean skin temperature and foot skin temperature, sweating rate, and metabolic heat production of one monkey (S:OBIE) during brief exposures of the whole body to 450-MHz CW microwaves (solid symbols) compared with control experiments (open symbols) when no microwaves were present. Ambient temperature (T_a) was constant at 34 °C. Individual points represent means of the preceding 5 minutes.

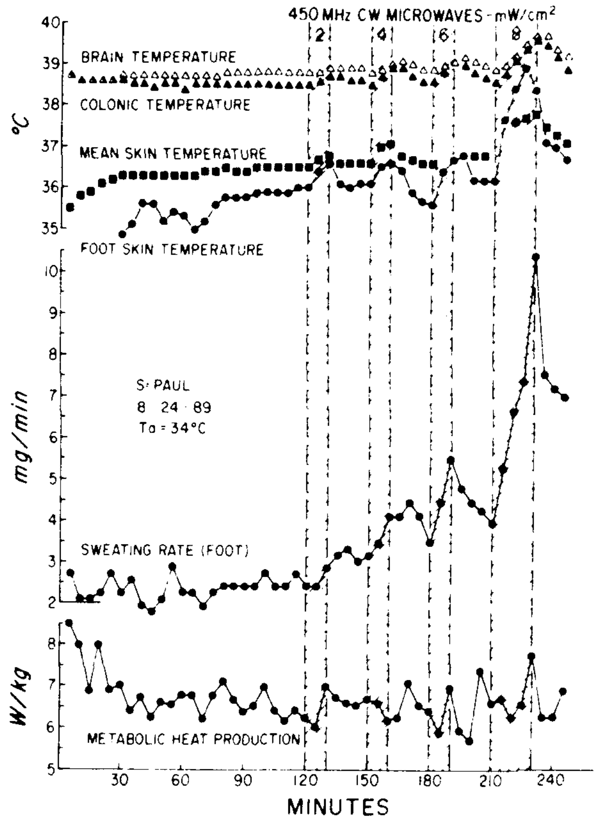


Figure 38. Representative experiment on one monkey (S:PAUL) to determine changes in body temperatures (brain, colonic, mean skin, foot skin), sweating rate, and metabolic heat production during brief exposures of the whole body to 450-MHz CW microwaves at an ambient temperature (T_a) of 34 °C.

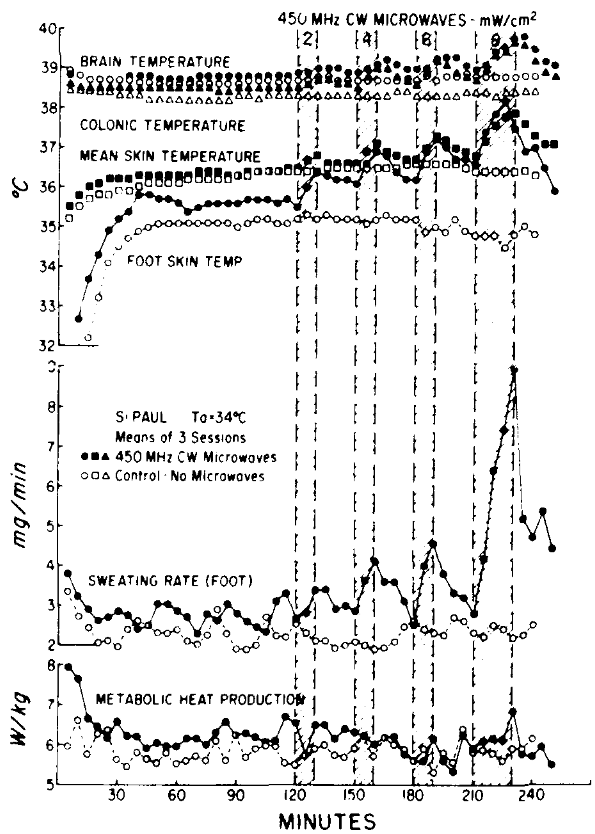


Figure 39. Mean changes (3 experimental sessions) in brain temperature, colonic temperature, mean skin temperature, foot skin temperature, sweating rate and metabolic heat production of one monkey (S:PAUL) during brief exposures of the whole body to 450-MHz CW microwaves (solid symbols) compared with control experiments (open symbols) when no microwaves were present. Ambient temperature (T_a) was constant at 34 °C. Individual points represent means of the preceding 5 minutes.

frequency, passive heating of the head was no greater than that of the animal's trunk.

Mean data from three experimental sessions conducted on S:Paul (solid symbols), together with mean control data for this monkey (open symbols) are summarized in Figure 39. In general, mean brain temperature (upper solid circles) was elevated no more during RF exposure than was T_{co} (upper solid triangles); both of these dependent variables showed significant elevation at the two highest power densities employed. Strong peripheral vasodilation of the foot skin was evident at the lowest power density presented (2 mW/cm^2), and all of the T_{ft} changes were sharp enough to have been sensed and appreciated by the monkey. Thermoregulatory sweating from the foot was well advanced by 4 mW/cm^2 and continued to increase to vigorous levels at 8 mW/cm^2 in the absence of any significant change in $\underline{M}$. It is clear that either foot vasodilation or sweating could have stimulated the peripheral thermoreceptors, thereby serving as an auxiliary cue to behavior (e.g., "My skin is warm" or "My skin is wet").

Discussion and Conclusions

During experimental sessions conducted at a constant T_a of 34 °C, all test animals exhibited sharp changes in foot skin temperature (indicative of vasodilation) and foot sweating during 10-min whole-body exposures to 450-MHz microwaves at power densities of 2 mW/cm^2 and above. Either of these responses were of a vigorous enough nature to have been sensed by the monkeys as peripheral thermoregulatory events. Whether either or both of these responses could serve as sensory cues to initiate thermoregulatory behavior is unknown, but the fact that they occurred at power densities virtually identical to those at which behavioral responses were altered in other experiments lends credence to the conjecture.

It is of considerable interest that, in this pilot experiment, the autonomic thermoregulatory responses of foot vasodilation and sweating occurred in a regular sequence as would be predicted from the thermoregulatory profile of the squirrel monkey (Fig. 1). Earlier data from our laboratory (8) showed a similar orderly mobilization of autonomic thermoregulatory responses at a T_a (32 °C) near the upper end of the TNZ by exposures to 2450-MHz CW microwave fields. In those experiments, foot vasodilation and sweating were mobilized at power densities of 10 to 20 mW/cm^2 (SAR=1.5 to 3.0 W/kg). In the present experiment, foot vasodilation was initiated in all animals at SAR=1.3 to 2.6 W/kg and sweating from the foot at SAR=2.6 to 5.2 W/kg. These preliminary data suggest a similarity in control of autonomic thermoregulatory responses between the two frequencies that must be further investigated and quantified in the future.

Nothing in the results of the present experiment contradicts the hypothesis that peripherally-manifested autonomic responses to resonant RF exposure could cue thermoregulatory behavior. The power density (or SAR) thresholds are of equivalent magnitude and the responses are vigorous and rapidly mobilized. It remains to demonstrate the concurrent incidence of both kinds of responses in behaviorally-thermoregulating animals. This is a very difficult type of experiment to perform because pure autonomic responses are easily obscured in active animals and T_a varies over time as must happen during behavioral thermoregulation, at least as we measure this response in our laboratory. A few preliminary attempts to conduct such combination experiments have met with only marginal success.

The overall conclusion derived from the four experiments conducted in this project is that both behavioral and autonomic thermoregulatory responses are mobilized in an orderly fashion when squirrel monkeys undergo whole-body exposure at the resonant frequency, 450-MHz CW microwaves. The threshold for alteration of thermoregulatory behavior is about 3 mW/cm^2, equivalent to a SAR of nearly 2 W/kg. Behavioral responses regulate the skin temperature at the normally-preferred level. Because of the deep penetration of the radiation at resonance, this regulation results in a stable hyperthermic offset or bias in the deep body temperature. This situation is identical to that which occurs during exercise. Although not yet studied, we presume that the magnitude of this offset will be a direct function of the energy deposited in the body, or SAR. Autonomic responses of peripheral vasodilation and sweating, manifested on the skin surface, are stimulated at SARs similar to the behavioral threshold, indicating the possibility that such responses could serve as auxiliary sensory cues to behavior.

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